Summer 1992

Metamorphism and Plutonism of the Mt. Buckindy – Snowking Region, North Cascades, Washington

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Western Washington University

METAMORPHISM AND PLUTONISM

OF THE MT. BUCKINDY - SNOWKING REGION,

NORTH CASCADES, WASHINGTON

by

Steve M. Fluke

Accepted in Partial Completion

of the Requirements for the Degree

Master of Science

Dean of Graduate School

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METAMORPHISM AND PLUTONISM OF THE MT. BUCKINDY - SNOWKING

REGION, NORTH CASCADES, WASHINGTON

A Thesis

Presented to

The Faculty of

Western Washington University

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ABSTRACT

The focus of this study is on the metamorphism, plutonism, and structures of the Mt. Buckindy-Snowking region of the North Cascades crystalline core.

In a 15 by 30 km region in the northwest portion of the crystalline core, Cretaceous plutons in a northwest-southeast belt intrude rocks of the Napeequa unit. Metamorphic grade in the country rock ranges from lower greenschist facies in the northwest to amphibolite facies in the southeast. Thermobarometry applied to the equilibrium assemblages garnet-biotite-muscovite-plagioclase and garnet-hornblende-plagioclase defines orogen-normal isobars varying from less than 4 Kb in the northwest to over 9 Kb in the south.

Plutons are granodioritic to tonalitic in composition and include, from southeast to northwest, the Downey Creek, Bench Lake, Cyclone Lake, and Jordan Lake plutons. Migmatite, composed of dikes and sills intruding country rock, formed during the emplacement of the Downey Creek and Bench Lake plutons. All of these plutons are presently undated except for a 73 Ma U/Pb zircon date for the Jordan Lake tonalite. However, the Downey Creek and Bench Lake plutons are inferred to be 95 to 96 Ma based on dates obtained from dikes in migmatite associated with the intrusion of these plutons.

The Downey Creek and Bench Lake plutons are interpreted to be syn-tectonic based on the following textural evidence: 1) dikes in the migmatite crosscut metamorphic foliations; 2) dikes in the migmatite display solid-state deformation textures; and 3) plutons display solid-state foliations parallel to the regional

metamorphic fabric. There is also mineralogic evidence of emplacement at depths equal to those reached during peak metamorphism. Geobarometry of the Bench Lake pluton, using the Al content of hornblende, yields pressures of 9.0 Kb (calibration of Schmidt, 1992) and 9.5 Kb (calibration of Hollister et al., 1987). Also, the occurrence of magmatic epidote supports emplacement at depths greater than 6 Kb. Country rock pressure is indicated to be 7-8 Kb from thermobarometry in this region.

A penetrative metamorphic foliation is recorded in all metamorphic and plutonic rocks except for the mostly undeformed Jordan Lake pluton. This fabric dominantly strikes northwest-southeast and dips steeply to moderately to the northeast. Mineral lineations within the foliation plane of the country rock generally trend northwest with a shallow to moderate plunge. Sparse kinematic indicators indicate non-coaxial, dextral shear, as found elsewhere in the crystalline core. Post-metamorphic sinistral shear is recorded in rocks along the west and southwest margin of the Triassic Marblemount meta-quartz diorite. This shear fabric is crosscut by the largely undeformed Jordan Lake pluton. But a sinistral shear zone is also found in the Jordan Lake pluton.

The findings of this study are consistent with an orogenic model involving dextral transpression within a magmatic arc; high-pressure, diachronous metamorphism is best explained by a magmatic loading model.

ACKNOWLEDGEMENTS

This project would not have been possible without the help and support of my main advisor, Ned Brown. He suggested the project, provided funding, and kept me focused throughout. I also owe a debt to my other advisors, Russ Burmester and Scott Babcock. They both contributed by providing enlightening views followed by countless references. Liz Schermer gave critical, thought-provoking reviews and helped interpret structures.

Field assistance in an alpine wilderness such as the North Cascades is a necessity. I am grateful to those that accompanied me on numerous week-long backpacking trips only to endure heavy loads and steep slopes for low pay. These hearty individuals include Mike Hettinga, Larry Fluke, Jennifer Fadden, Paul Riley, and Matt Nelson. I hope the rugged beauty of the North Cascades made it worthwhile for y'all as it did for me.

Dan McShane, Bernie Dougan, and Kathleen Duggan had me surrounded with adjoining field areas in the crystalline core. They were always available for thoughtful discussions of Cascades geology and to compare notes.

The graduate school logistics were smoothed out and made bearable by George Mustoe, Vickie Critchlow, Pattie Blake, and Chris Sutton.

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INTRODUCTION

General Statement

In this study I have examined rocks in an area within the crystalline core of the North Cascades, Washington (Fig 1). The crystalline core and the related British Columbia Coast Plutonic Complex consist of high grade metamorphic rocks, migmatites, and plutons resulting from a major mid-Cretaceous orogenic event.

The study area is located in Washington State almost entirely within the Glacier Peak Wilderness and includes approximately 100 square miles in the vicinity of Mt. Buckindy and Mt. Snowking (Fig 2). Several mid- to late-Cretaceous plutons and their host terranes provide a petrologic, geochronologic, and structural record of the orogeny. Findings of the present study combined with data from adjacent areas help to establish regional petrologic patterns that can be used to test current models for the origin of the crystalline core and the Coast Plutonic Complex.

Regional Geology

Rocks extending from northern Washington to southeast Alaska belong to one of the earth's largest plutonic/metamorphic belts, the Coast Plutonic Complex (CPC). The CPC is composed of Mesozoic and Tertiary plutons, many of which were emplaced at deep crustal levels (>6-8 Kb) as evidenced by the presence of magmatic epidote and high Al hornblende (Hammarstrom and Zen, 1986). Metamorphic rocks

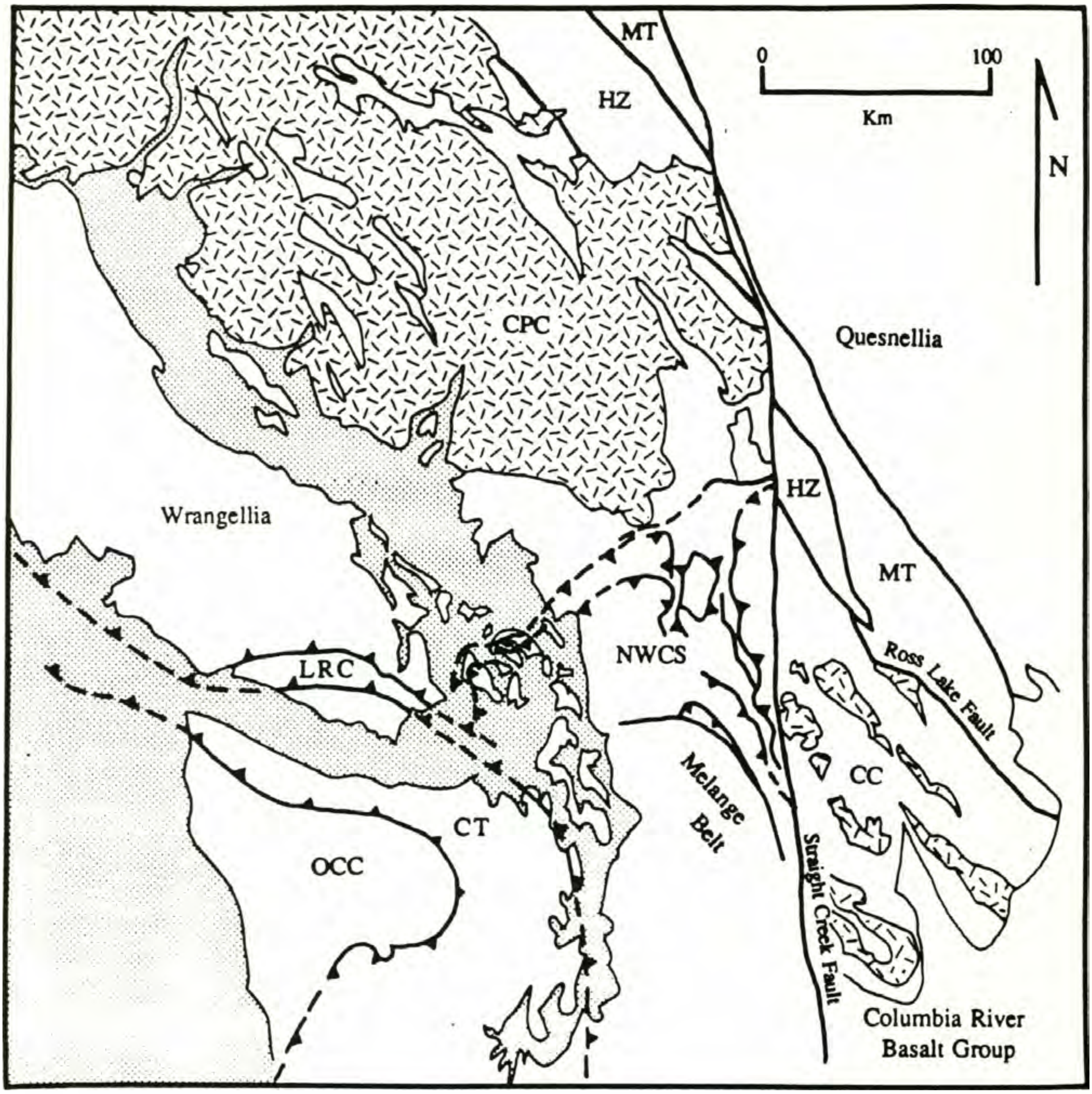


Figure 1. Generalized map of the major terranes of northwest Washington and southwest British Columbia. Mesozoic igneous rocks are delineated by hatched patterns. MT = Methow terrane; HZ = Hozameen terrane; CPC = Coast Plutonic Complex; CC = Crystalline Core; NWCS = Northwest Cascades System; LRC = Leech River Complex; CT = Crescent terrane; and OCC = Olympic Core Complex. (Modified from Brown and Talbot, 1989.)

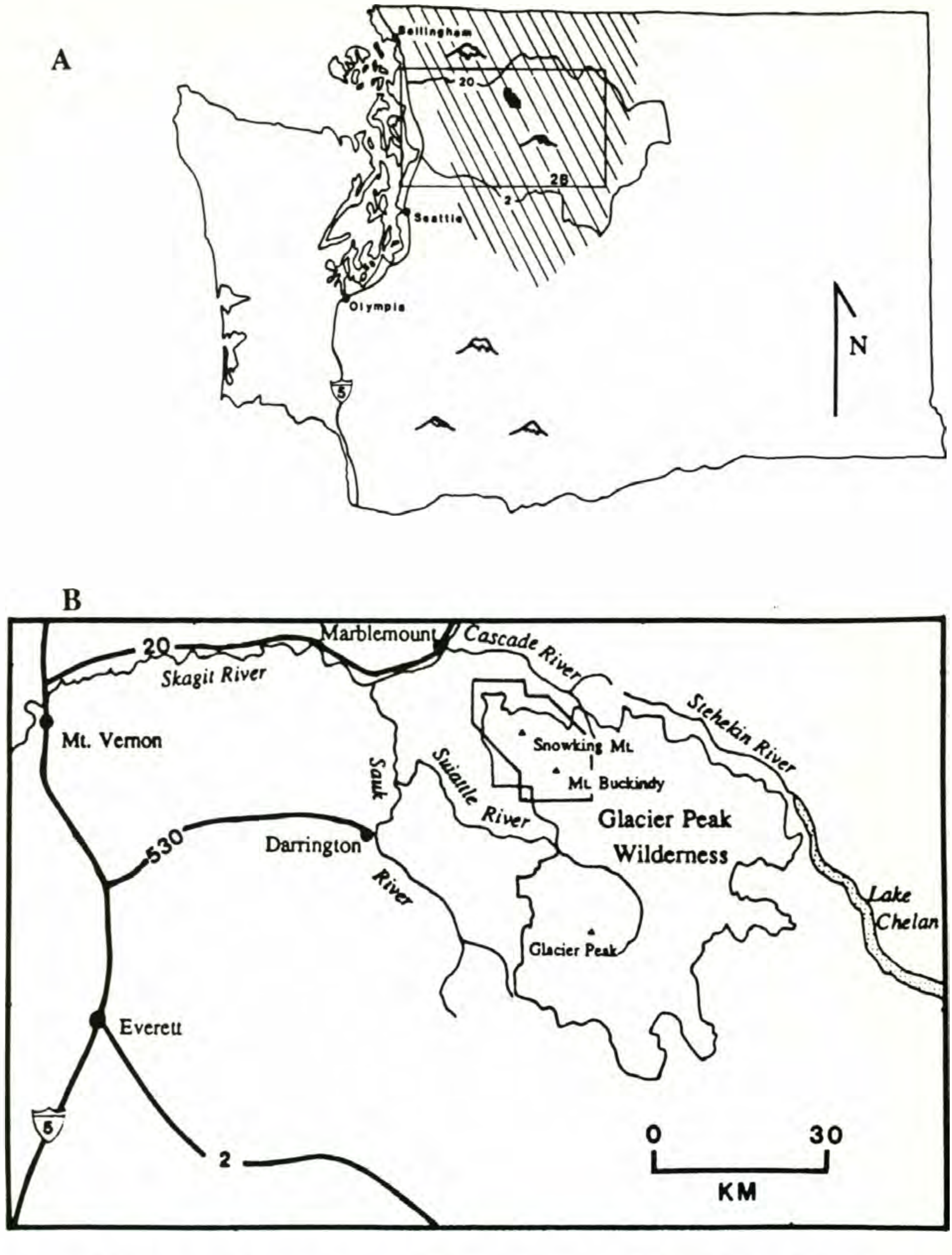


Figure 2. Geographic location maps of the study area. A) Washington State with hatch marks showing approximate extent of the North Cascades. B) Regional map of the study area showing the Glacier Peak Wilderness Area and major access routes and geographic features. (Modified from Ford et al., 1988.)

are relatively sparse throughout the CPC, but dominate the southern portion in Washington.

The crystalline core (CC) is recognized as the southern extension of the Coast Plutonic Complex, now offset by 90-190 km on the Eocene, dextral strike-slip, Straight Creek-Frazer River fault (Misch, 1977; Vance, 1992)(Fig 1). The fault juxtaposes rocks of the Northwest Cascades System (NWCS) to the west of the CC. The NWCS is a melange of oceanic rocks that have undergone a high-P, low-T metamorphism. The Ross Lake fault separates the CC from the Permian-Jurassic Hozameen terrane to the north and the Jurassic-Cretaceous Methow basin rocks to the east (Fig 1). Rocks of the CC are presently divided into four tectonostratigraphic terranes (Tabor et al., 1989)(Fig 3). The terranes are characterized by distinct lithologic assemblages, but, cannot everywhere be shown to have fault contacts due to post-accretionary deformation and metamorphism.

The terranes, mostly composed of metamorphosed marine sedimentary and volcanic rocks, were in place by the mid-Cretaceous. They contain pre-accretionary plutons and volcanic rocks as old as 220 Ma (Mattinson, 1972; Cary, 1990). A major mid- to late-Cretaceous metamorphic event is bracketed by zircon ages of pre-, syn-, and post-tectonic plutons (Mattinson, 1972; Walker and Brown, 1991). These plutons range from granodiorites to gabbros (Ford et al., 1988), have emplacement dates of early Cretaceous to Tertiary, and show evidence of deep to shallow levels of emplacement. Metamorphic rocks include schists and gneisses ranging in grade from lower greenschist to upper amphibolite facies. Pressures of up to 9 Kb have been

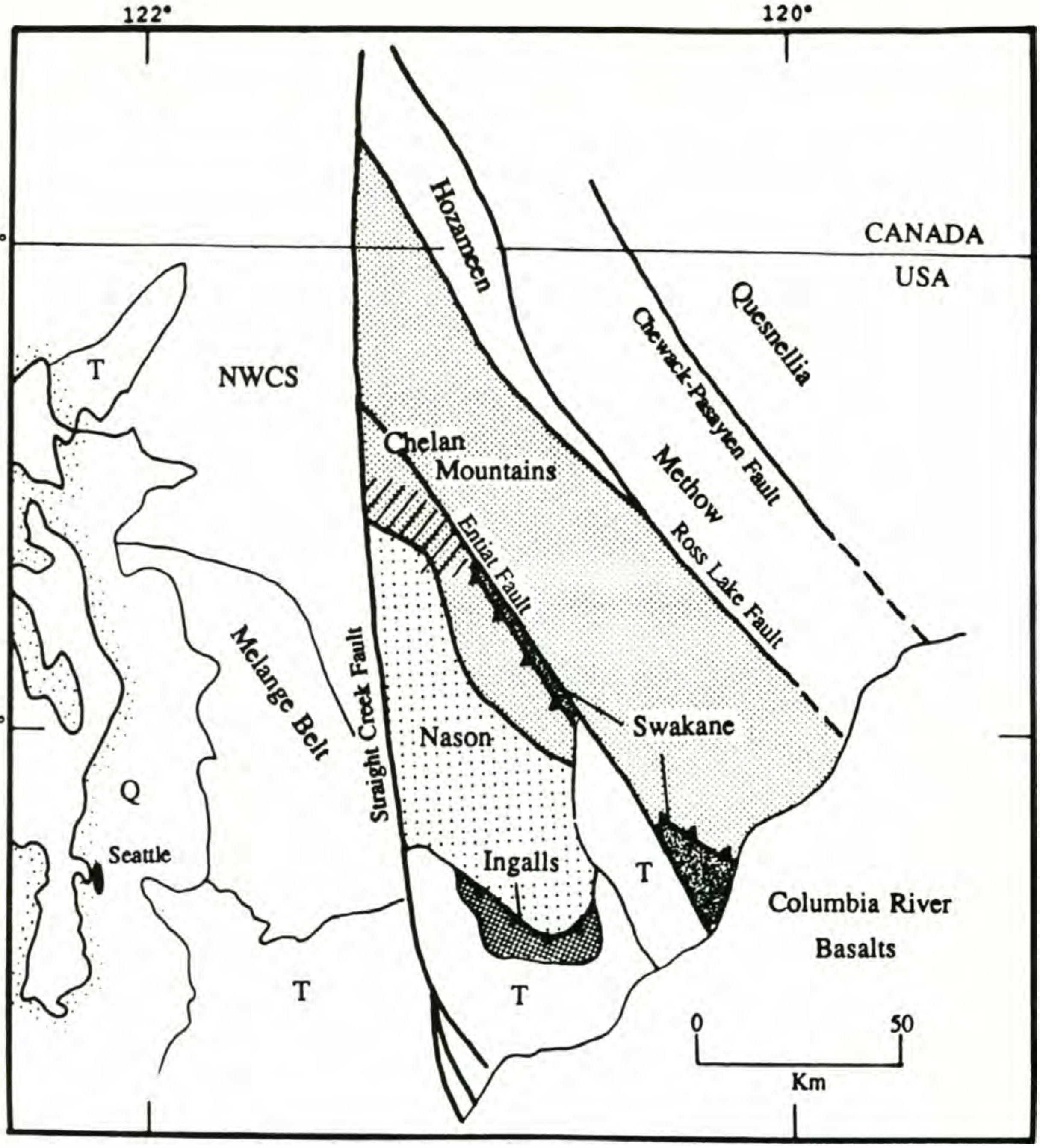


Figure 3. Cartoon of the four terranes within the crystalline core (stippled) and the major terranes and units surrounding them. Study area is hatched. NWCS = Northwest Cascades System; T = Tertiary sedimentary and volcanic deposits; Q = Quaternary unconsolidated deposits. (Modified from Tabor et al., 1989.)

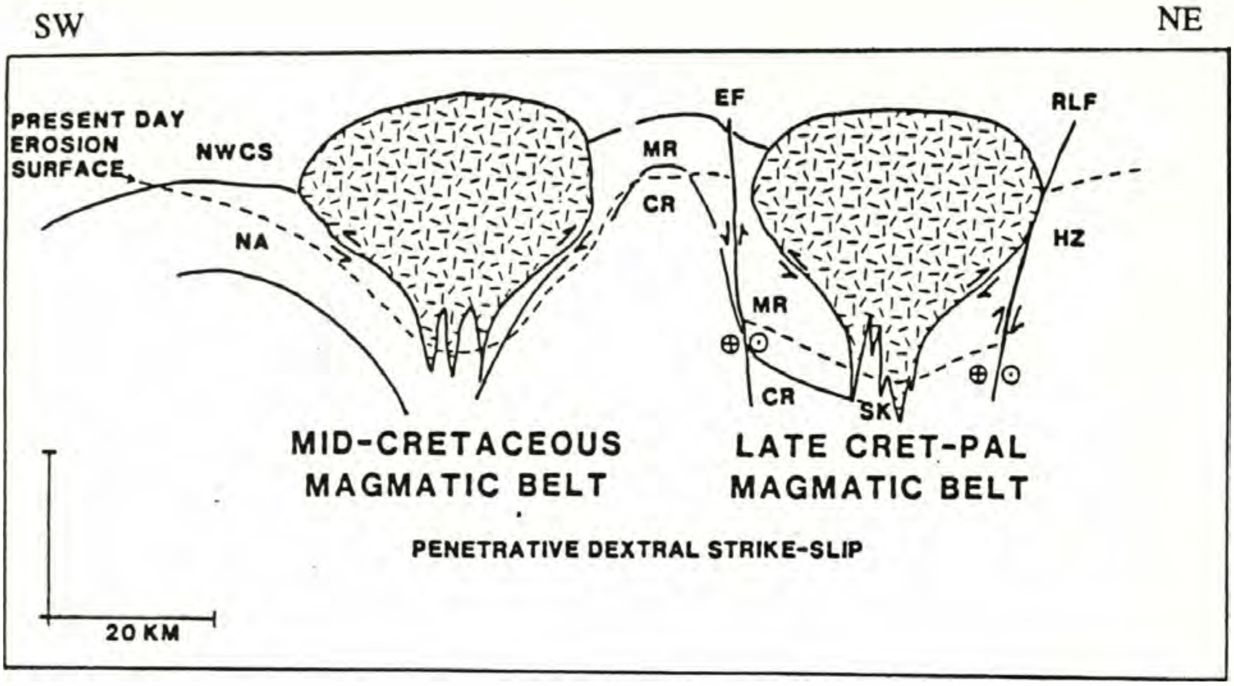
recorded (Whitney and McGroder, 1989). Most of the CC displays a strong fabric that developed during the metamorphism.

Orogenic Models

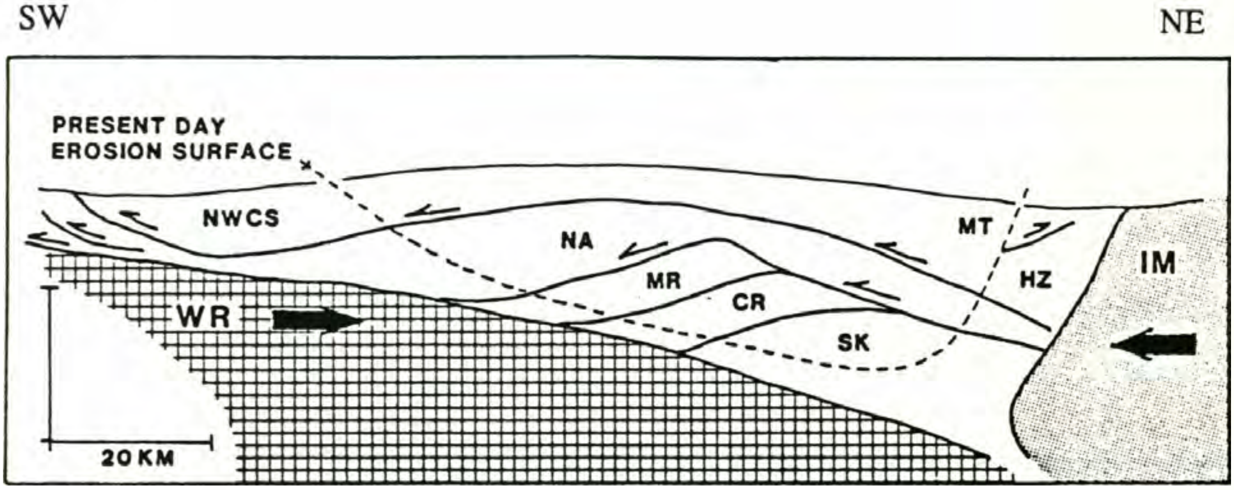
Controversy regarding the origin of the CPC is centered on the significance of: 1) the accretion of the Wrangellia terrane to North America, 2) thrusting of the NWCS during metamorphism of the CC, and 3) the generation of large volumes of magma during orogeny.

In one model, Andean-style arc magmatism (Armstrong, 1988) and coeval transpression of previously accreted terranes (Brown and Talbot, 1989) is considered to be ongoing during orogenesis. NWCS thrusting is inferred to be orogen-parallel and not the direct cause of metamorphism in the CC (Brown, 1987). Importance is placed on the emplacement of magma as an agent of metamorphism. As magma rises in the crust, country rock is metamorphosed to high pressures by displacement to deep crustal levels in order to make room for the rising magma (Brown and Walker, 1991)(Fig 4A). Isostatic rebound following uplift and erosion raises these deeply buried rocks to the present day surface.

In another model, crustal loading, regional metamorphism, and magmatism result from contractional thrusting related to the collision of Wrangellia with North America (Davis et al., 1978; Monger et al., 1982; Zen, 1988; McGroder, 1991)(Fig 4B). The Hozameen and Methow basin rocks are thought to be the root of nappe structures culminating in the NWCS (Brandon and Cowan, 1985; McGroder, 1991).



A



B

Figure 4. Model cross-sections of the North Cascades during orogenesis showing different interpretations of the cause of high pressure metamorphism. A) Localized pressures due to magmatic loading. (From Brown, 1990.) B) Regional loading due to thrust stacking. (Based on McGroder, 1991.)

IM = Intermontane Superterrane; WR = Wrangellia; SK = Skagit Gneiss; CR = Cascade River Schist; MR = Mad River terrane (now included with Chelan Mts. terrane); NA = Nason terrane; HZ - Hozameen terrane; MT = Methow terrane; NWCS = Northwest Cascades System; RLF = Ross Lake fault; EF = Entiat fault.

Orogen-normal thrusting provides a means for crustal thickening necessary for the high-grade rocks of the CC (Monger et al., 1982; Brandon et al., 1988; McGroder, 1991).

Study Area

The study area is located predominantly within the Chelan Mountains terrane although the southwestern portion includes part of the Nason terrane (Fig 5). The Chelan Mountains terrane, as defined by Tabor et al. (1989), is regionally continuous and is composed of many lithologic units. The Triassic Marblemount meta-quartz diorite (Misch, 1966; Mattinson, 1972) is considered to be composed of arc-related plutons (Cary, 1990). Metavolcanics and clastics of the Cascade River unit (Tabor, 1961; Misch, 1966; Dragovich, 1989; and Dougan, 1992) are probably arc-related fan deposits. Chert-rich oceanic rocks also included within the Chelan Mountains terrane (Tabor et al., 1988) are represented by the Napeequa unit.

The Nason terrane in the study area is composed of the Chiwaukum schist, derived from a pelitic to psammitic protolith (Tabor et al., 1988).

A northwest to southeast group of plutons in the study area was first delineated by Bryant (1955). These plutons intrude the regionally metamorphosed Napeequa Schist of the Chelan Mountains terrane and the Chiwaukum Schist of the Nason terrane. Plutons include the Jordan Lake tonalite, the Cyclone Lake granodiorite, the Bench Lake tonalite, and the Downey Creek granodiorite. Only the 73 Ma Jordan Lake pluton has been dated by U/Pb zircon (Walker and Brown, 1991).

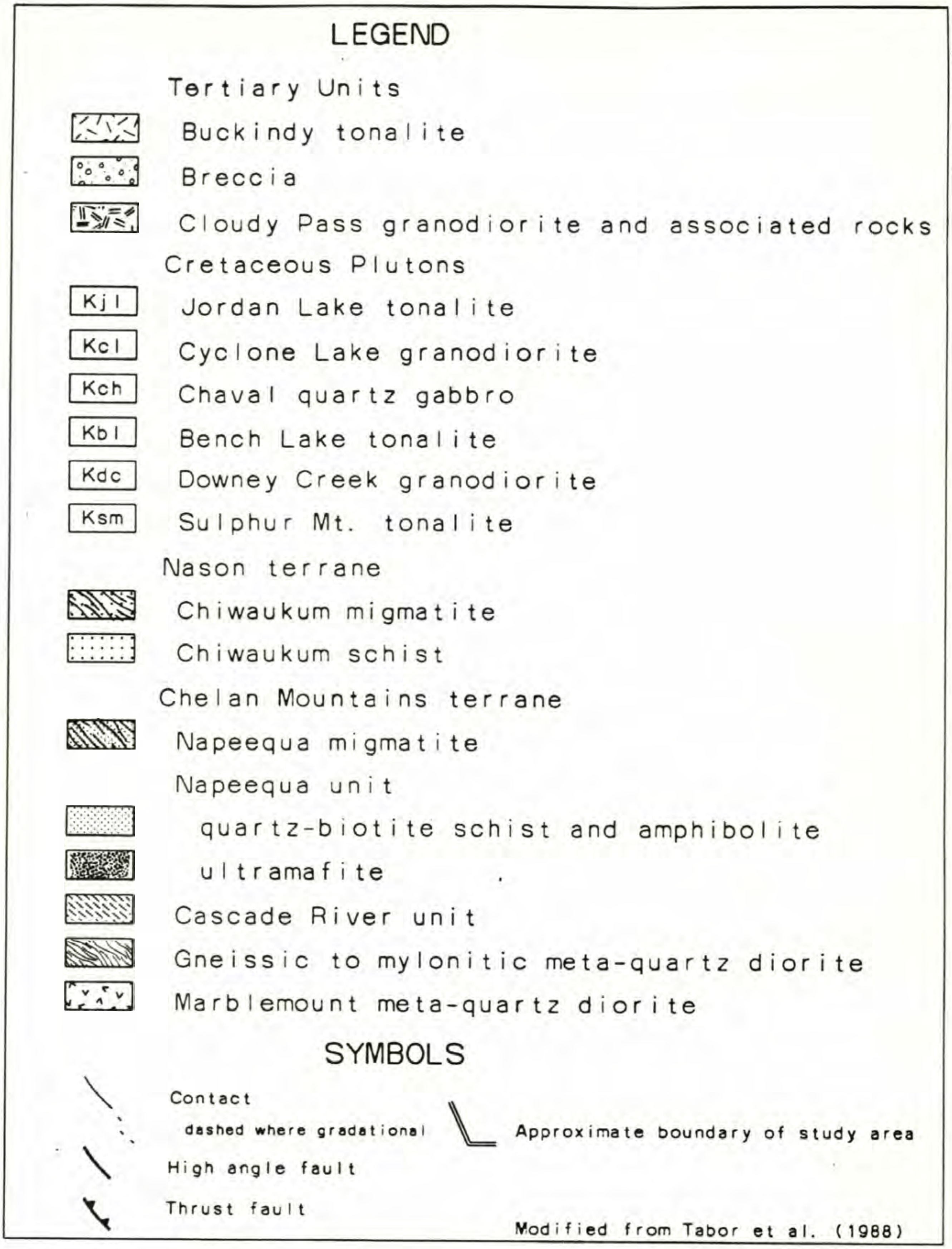
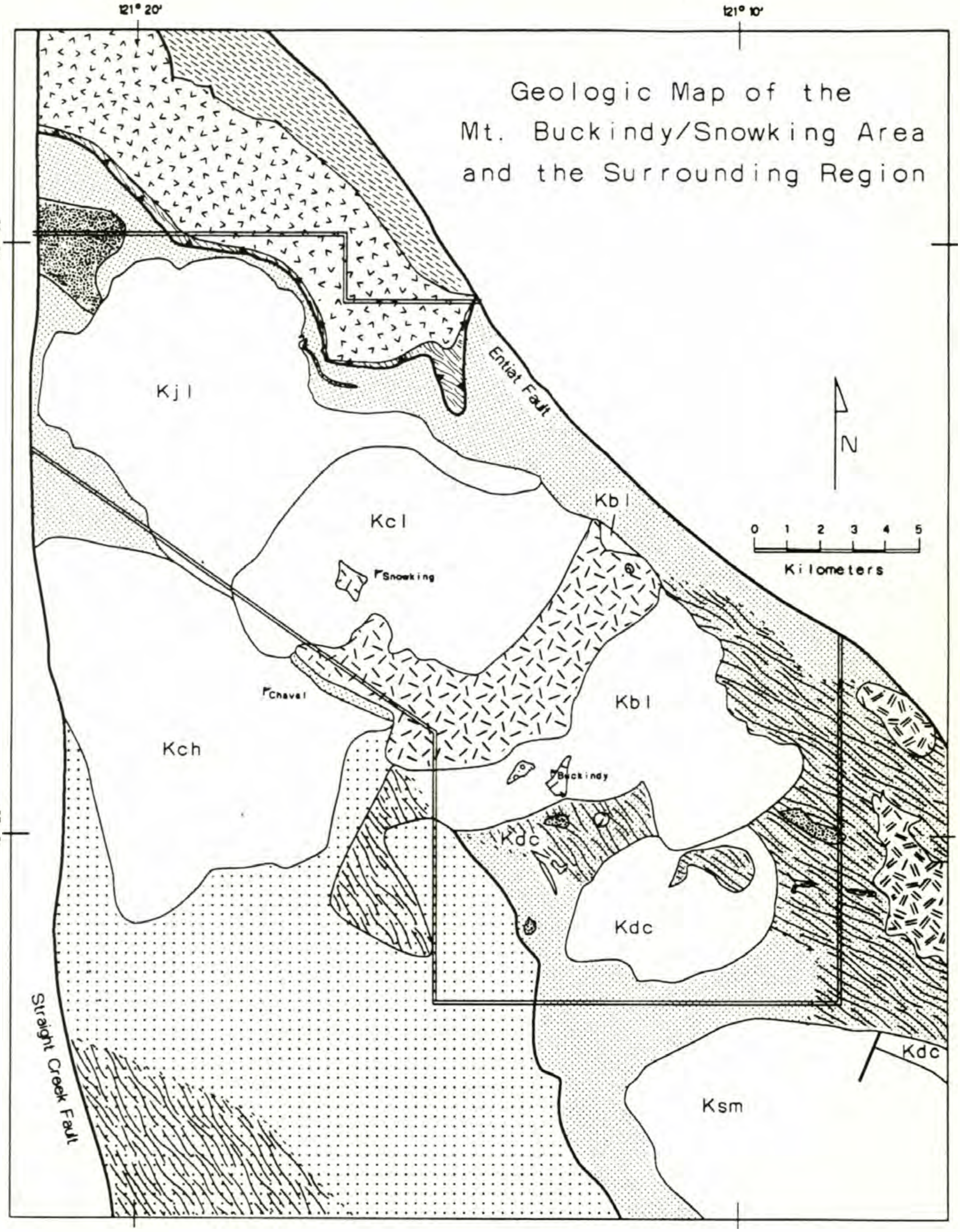


Figure 5. Generalized geologic map of the study area and surrounding region.


121° 20'
121° 10'
Geologic Map of the
Mt. Buckindy/Snowking Area
and the Surrounding Region
48° 30'
48° 20'
Kjl
Kcl
Kbl
Kch
Kdc
Ksm
Snowking
Chavel
Buckindy
Entiat Fault
Straight Creek Fault
N
0 1 2 3 4 5
Kilometers

Metamorphism that culminated during deformation ranges from greenschist facies in the northwest to upper amphibolite facies in the southeast.

Statement of Problem

The specific objectives of this project are: 1) to obtain samples of plutonic rocks in the area for U/Pb dating; 2) to establish a metamorphic history; 3) to understand the relationship between the plutonism and metamorphism; and 4) to describe structural features relating to emplacement of the plutons and deformation in the region.

The general objective, as part of an ongoing project at WWU involving faculty and Masters students, is to increase our understanding of the orogenic evolution of the Coast Plutonic Complex and the North Cascades crystalline core.

LITHOLOGIC DESCRIPTIONS

Introduction

Descriptions of rock units, samples collected, contacts, and field relationships are presented in this section. Place names mentioned in this text, sample localities, and geology can be found on the map of Plate 1. Mineral assemblages for samples collected are listed in Appendix 1. Geologic contacts are taken from Tabor et al. (1988) with some modifications as noted in this report.

Units of the Chelan Mountains Terrane

Napeequa Unit

The Napeequa Schist is the dominant country-rock unit in the study area and consists of a variety of lithologies. These include fine to medium grained quartz-biotite schist, quartzite, amphibolite, and carbonaceous to micaceous phyllite. The rock commonly crops out as biotite-, hornblende-, or quartz-rich schist interlayered at the scale of centimeters to tens of meters. Compositional layering probably reflects relict bedding. Ultramafic rock crops out as massive to foliated pods and layers of serpentinite and as thin layers of actinolite and talc schist concordant with the regional foliation. Rare marble also occurs as layers concordant with regional foliation. Metamorphic grade varies from greenschist facies in the northwest to upper amphibolite facies in the southeast. A well developed foliation in the schist is defined by alignment and segregation of phyllosilicates, quartz and feldspar, and hornblende. Isoclinal folding is evident in addition to an overprinting of crenulation cleavage on S-surfaces.

Protoliths of the Napeequa unit were likely deposited in an oceanic setting. The amphibolites and quartz-biotite schists are possibly derived from oceanic basalt and cherty to marly oceanic sediments respectively. Slivers of ultramafics are presumed to be mantle derived, fault bounded blocks emplaced before accretion of the terrane.

Quartz-biotite schist - The predominant rock type of the Napeequa unit is a quartz-biotite schist. The rock is a brown to dark gray, fine to medium grained quartzose biotite-hornblende-garnet schist or biotite-muscovite-garnet schist. The characteristic metamorphic mineral assemblage is quartz, plagioclase, biotite, muscovite or amphibole, garnet, chlorite, epidote, sphene, and graphite with trace rutile and opaque minerals. Outcrops are homogeneous with some biotite, hornblende, or quartzofeldspathic layers at the millimeter to centimeter scale. The schist locally grades into quartzite or amphibolite.

A well developed foliation is defined by preferred orientation of phyllosilicates, elongate quartz and plagioclase grains, quartz ribbons, and hornblende. Phyllosilicates are fine to coarse grained, subhedral to anhedral, and commonly organized into laminae defining a gneissic foliation. Amphiboles are subhedral to euhedral elongate grains, average 1-2 mm in length, and display garbenscheifer or rarely lineated textures. Garnets usually display pre- or syn-kinematic growth textures, are mostly poikiloblastic or highly embayed, and some are partially replaced by chlorite (Fig 6).

Phyllite - Micaceous to carbonaceous phyllite is located in the northwestern region of the study area, north of the Jordan Lake pluton. The micaceous phyllite is most abundant and consists of a light gray to light green muscovite-chlorite phyllite. The characteristic mineral assemblage is quartz, albite, biotite, muscovite or actinolite, chlorite, epidote, sphene, and graphite with trace calcite, rutile, and opaques.

Gray to black carbonaceous phyllite crops out locally and contains the assemblage quartz + plagioclase + graphite. Idioblastic pyrite crystals up to 2 mm overprint the foliation. The phyllites are well foliated and often display crenulation cleavage on the S-surfaces.

Amphibolite - Dark green to gray amphibolite crops out as discrete layers within the quartz biotite schist and as locally continuous layers tens of meters thick. The characteristic metamorphic mineral assemblage is hornblende, plagioclase, quartz, epidote, and rutile. The rock is well foliated as defined by aligned amphiboles and alternating layers, 0.5-10 mm thick, of amphibole and plagioclase (Fig 7). Hornblende displays garbenscheifer texture or less common mineral lineations.

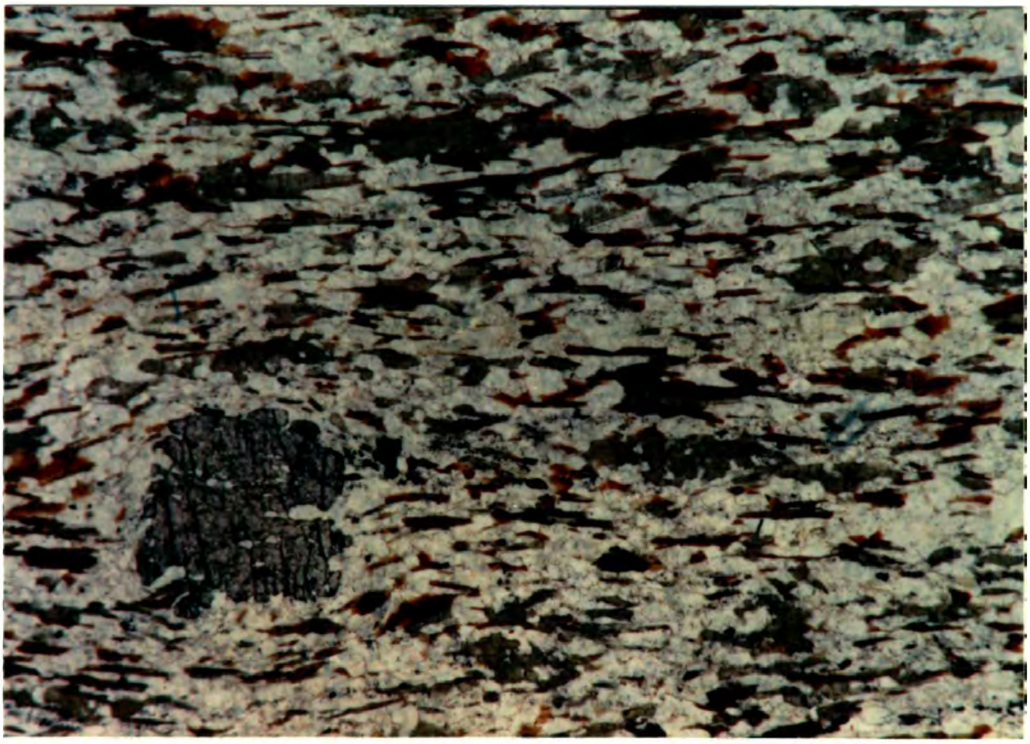


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Figure 6. Photomicrograph of typical quartz-biotite schist with garnet and hornblende of the Napeequa unit (specimen 174-24). Section is cut normal to foliation and parallel to a mineral lineation defined by biotite and hornblende. Plane polarized light.

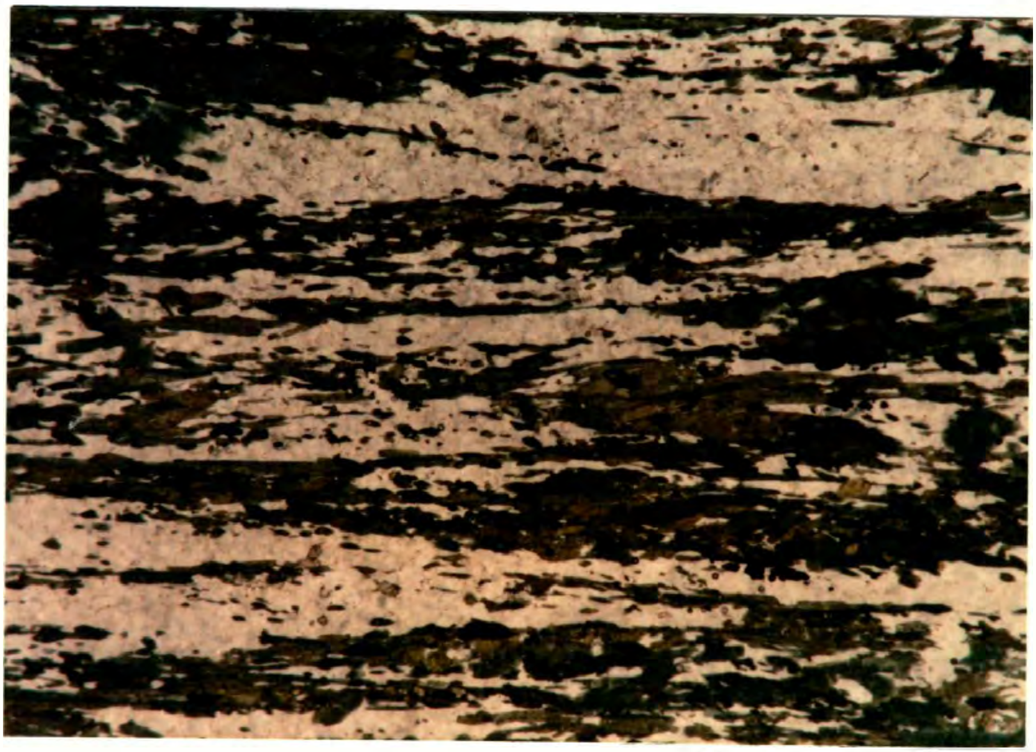

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Figure 7. Photomicrograph of typical amphibolite of the Napeequa unit showing interlayered elongate hornblende aggregates and plagioclase (specimen 174-6b). Section is cut normal to foliation and parallel to a mineral lineation defined by hornblende. Plane polarized light.

Marble - Rare outcrops of white to gray, coarse grained marble layers, up to 2 m thick, are concordant with the regional foliation. The marble varies from pure calcite to siliceous marble. Mineral assemblages include calcite, quartz, tremolite, and epidote with trace sphene and biotite. The marble layers are in sharp contact and concordant with the foliation of the surrounding schist, but can also be found to pinch out in places.

Thin sections reveal calcite and undulose, highly recrystallized quartz partially segregated and in equal proportions. Tremolite is found as elongate euhedral to subhedral grains concentrated in quartz rich layers.

Ultramafite - Ultramafic rocks of the Napeequa unit are serpentinite, chlorite-actinolite schist, and talc schist. The serpentinite are dark green to black and rusty brown to orange on weathered surfaces. Outcrops are large massive pods and massive to foliated layers concordant with the surrounding schist.

A large serpentinite body is located in the northwest region of the study area on the ridge between Jordan and Boulder Creeks. A thin sections reveals a matted aggregate of fine-grained antigorite (97%) with scattered fine-grained (dusty) and less abundant coarse-grained opaques. Bryant (1955) reports the sparse occurrence of olivine and pyroxene in the outcrop. He also reports the occurrence of talc near the serpentinite contact with the Jordan Lake pluton.

Serpentinite near Granite Lakes contains the assemblage antigorite, orthopyroxene, and opaques. In thin section, relict primary coarse grains of orthopyroxene are evident. The relict grains are approximately 90% altered to serpentine along cleavage planes and grain boundaries, leaving only thin slivers too small to identify microscopically. It is likely that these grains are primary orthopyroxene that have undergone serpentinization (Fig 8).

In the higher grade southern part of the study area, ultramafic rocks contain the assemblage forsterite, talc, antigorite, magnesite, opaques, and chlorite. Forsterite occurs as subhedral elongate grains aligned with the regional foliation. The forsterite is serpentinized between grains and within grain fractures. Talc is found as fine grained radiating needles and cryptocrystalline clumps segregated from forsterite, and as euhedral grains with forsterite (Fig 9).

Forsterite and talc are the expected equilibrium assemblage derived from the prograde metamorphism of antigorite at temperatures above approximately 550 °C (see metamorphic section). Evidence for a metamorphic origin of the forsterite includes: metamorphic textures of forsterite such as the preferred alignment of elongate grains and the absence of kinking and undulose extinction; the apparent textural equilibrium of talc with forsterite; and the apparent transformation of serpentinite, with relict peridotite, in lower grade rocks to (meta)peridotite in higher grade rocks (Vance and Dungan, 1977).

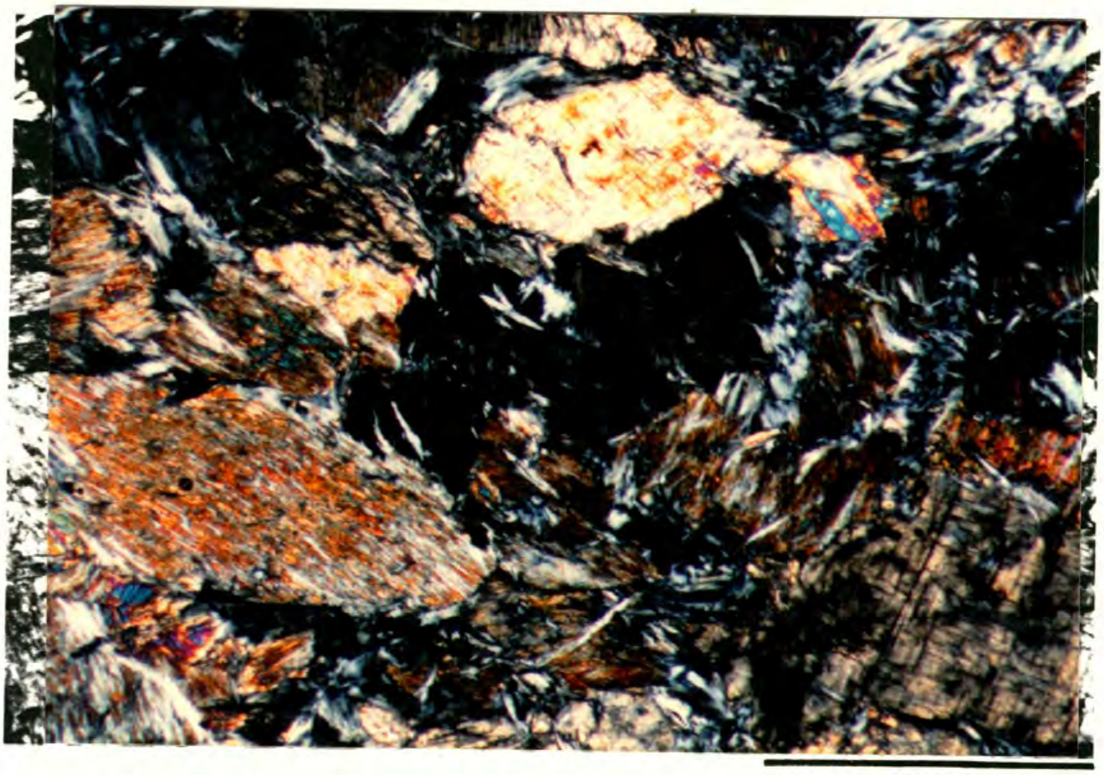

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Figure 8. Photomicrograph of serpentinite with relict orthopyroxene. Note 90° cleavage of grain in bottom right and antigorite growth between cleavage and grain boundaries (specimen 174-127). Crossed nicols.

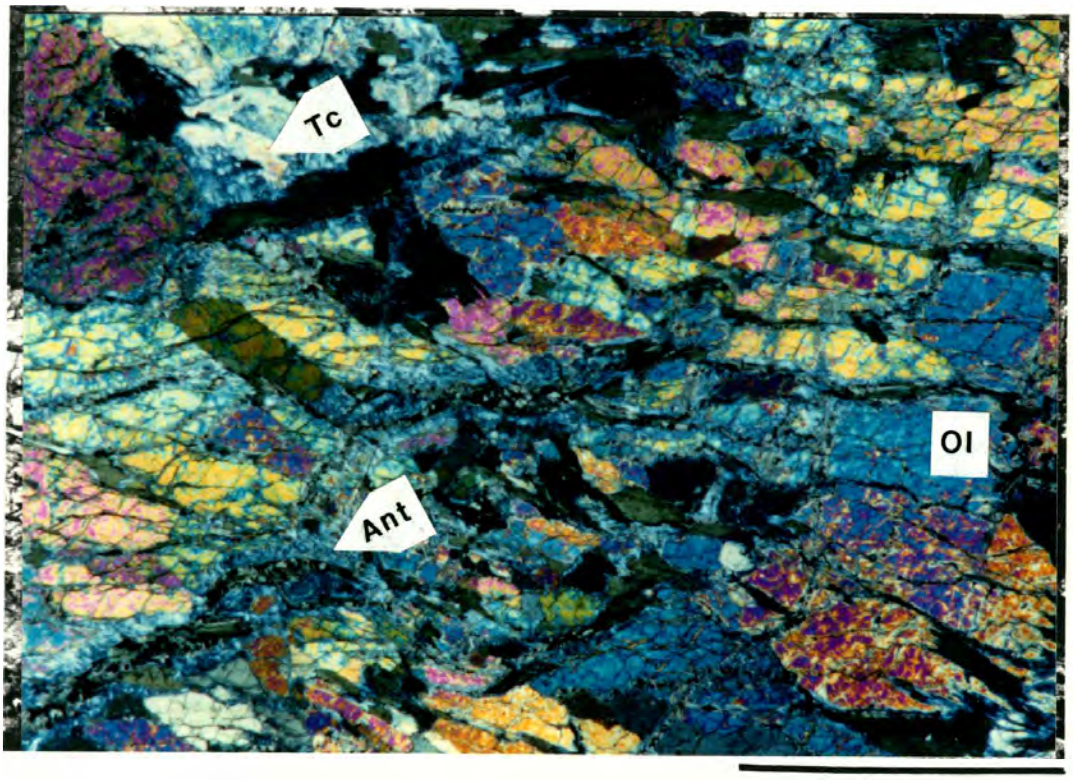

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Figure 9. Photomicrograph of ultramafic rock from the southern high grade part of study area (specimen 174-20). Olivine displays a preferred alignment of elongate grains and lacks kinking and undulose extinction. The coexistence of olivine and talc are probably the result of deserpentinization. They are seen here partially replaced by antigorite. Crossed nicols. Ol-olivine, Tc-talc, Ant-antigorite.

Talc schist and chlorite-actinolite schist crop out as thin concordant layers (< 1 m) within the quartz-biotite schist and as larger bodies associated with serpentinites. Near Spire Lake, talc schist in a large outcrop (approximately 20 m thick) is well foliated. Talc and possibly tremolite are aligned and in places display a fibrous habit.

Chlorite-actinolite schist is dark green with garbenscheifer actinolite blades up to 1 cm long in a matrix of chlorite.

Marblemount meta-quartz diorite

The Marblemount meta-quartz diorite (MMQD) is a light colored, medium grained, greenish diorite and tonalite that crops out in the northern part of the field area. This unit is part of a northwest-southeast belt of Triassic plutons including the Dumbbell pluton of the Holden Lake area and possibly the Magic Mountain gneiss to the southeast (Mattinson, 1972). Rock generally is massive, but contains localized foliation and shear fabric. Igneous minerals include quartz, plagioclase, biotite, muscovite, and hornblende. Greenschist facies metamorphism is evident in most of the pluton from the common occurrence of metamorphic actinolite, albite, epidote, chlorite, and biotite. The metamorphic grade increases to the southeast where biotite, hornblende, and oligoclase isograds can be mapped (see metamorphic section).

Concordant isotopic U/Pb ratios for zircons give an age of 220 Ma (Mattinson, 1972). Metadacite of the Cascade River unit, an arc-derived clastic and volcanic deposit, gives a similar age of 220 Ma (Cary, 1990). Geochemistry, field relations, and ages of the Marblemount and Cascade River units suggest that they are derived from the same magmatic arc (Babcock and Misch, 1988; Cary, 1990), and represent subarc and suprarc material respectively.

Mylonitic meta-quartz diorite - Along the southern margins and locally within the pluton, MMQD grades into well foliated to mylonitic meta-quartz diorite. A zone approximately 50 m thick of green, well foliated, fine to medium grained mylonite is located along the southwestern contact of MMQD grading into the gneissic meta-quartz diorite (above) and the Napeequa unit (below). The fine grained mylonite is generally sheared beyond recognition of a distinct protolith (ultramylonite), but the coarser grained rock displays relict igneous plagioclase (Fig 10). The characteristic mineral assemblage is quartz, epidote, plagioclase, chlorite, muscovite, biotite, and calcite with trace rutile, sphene, and opaques. Quartz ribbons and plagioclase augen are interlayered with fine grained muscovite, epidote, chlorite, and calcite. North by northwest trending and shallowly plunging mineral lineations can be found in the coarser grained mylonite. The mylonite is discussed more thoroughly in the structure section.

Gneissic meta-quartz diorite - A gneissic meta-quartz diorite crops out at the southern margin of MMQD, on the ridge between Kindy and Found Creeks, and as a gradation between undeformed Mmqd and the green mylonite. Foliation is defined by quartzofeldspathic and mafic minerals in layers up to 2 mm thick. The characteristic

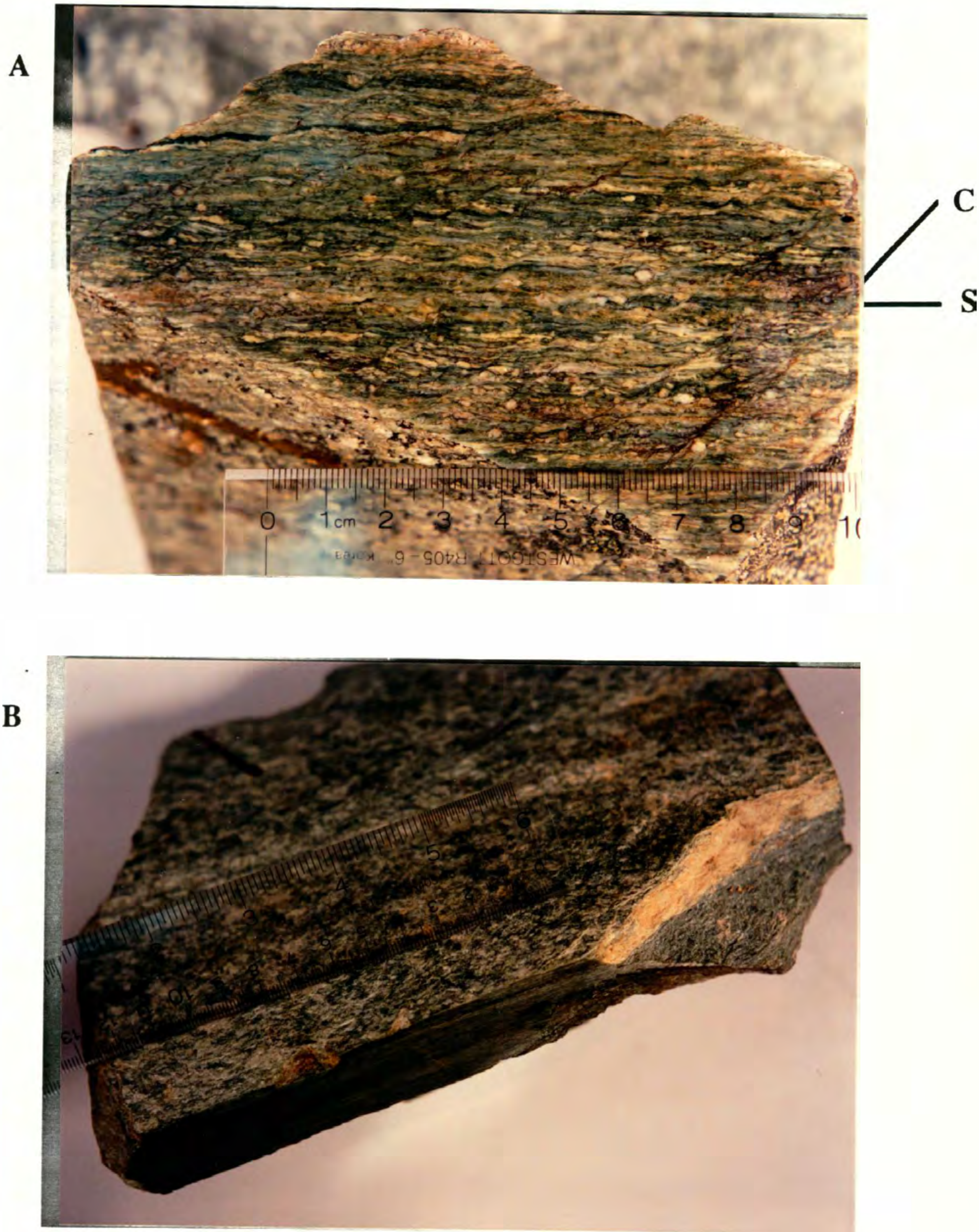

Figure 10. Mylonite found in the southwestern margin of the Marblemount meta-quartz diorite. A) Coarse grained mylonite with S-C structures indicating sinistral shearing. B) Fine grained ultramylonite with one plane of schistosity.

mineral assemblage is quartz, plagioclase, amphibole, epidote, chlorite, and biotite with a trace of rutile and sphene.

Near Granite lakes, elongate, euhedral to subhedral hornblende up to 2 cm long is concordant with the foliation and displays a weak mineral lineation (Fig 11). Fine grained actinolite needles splay out from the hornblende and also form aggregates crosscutting the foliation. Textures suggest growth of hornblende during peak metamorphism followed by minor recrystallization to actinolite during a retrograde event (Fig 12).

On the ridge between Found and Kindy creeks, weak foliation in MMQD is defined by aligned biotite and chlorite, hornblende, quartz ribbons, and fine grained epidote. Plagioclase and quartz display highly recrystallized and augen textures. Microprobe analysis of one plagioclase grain reveals a core An% = 8 and a rim An% = 19, suggesting metamorphic growth within the peristerite gap (see metamorphic section).

Nason Terrane

Chiwaukum schist

The Chiwaukum schist, which extends well to the south beyond the study area, was examined only along the northeast ridge of Green Mt. The unit is predominantly

Figure 11. Gneissic Marblemount meta-quartz diorite in area above Granite Lakes on peak 6401'. Elongate hornblende porphyroblasts are very weakly aligned here, but are better aligned nearby.

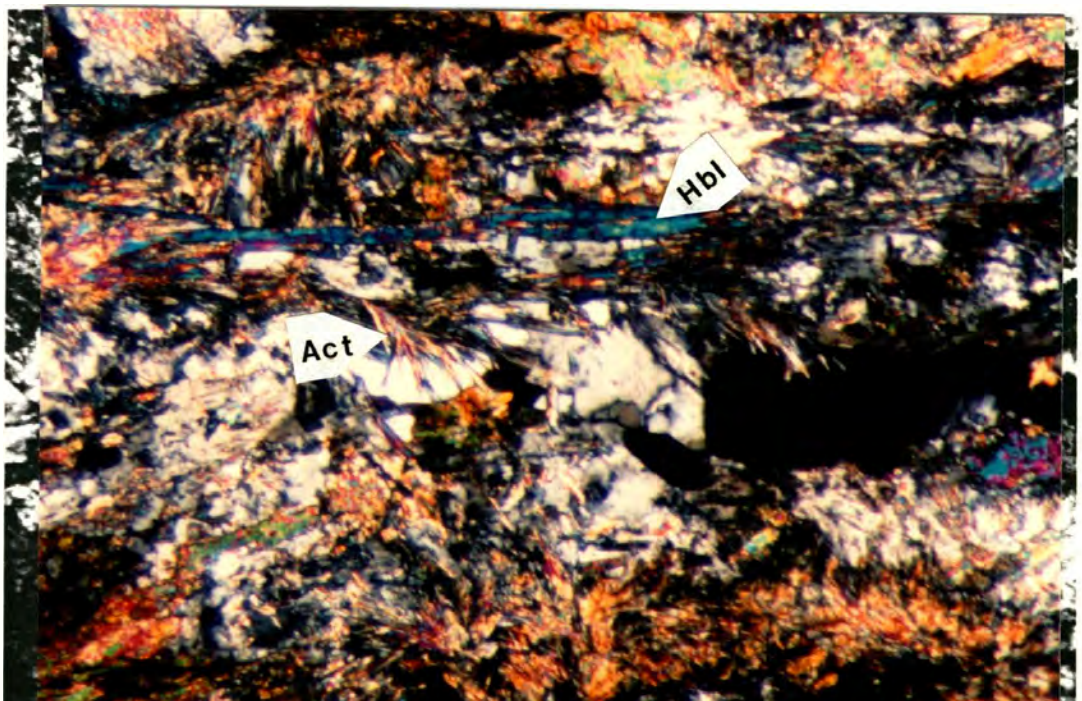

Figure 12. Photomicrograph of gneissic Marblemount meta-quartz diorite with strong lineation (near rock of Fig 11). Section is cut normal to foliation and parallel to elongate hornblende crystals (Hbl) that define a mineral lineation. Post-kinematic actinolite needles and aggregates (Act) cross-cut the foliation (specimen 174-114a). Crossed nicols.

a pelitic schist with less abundant amphibolite and quartzite, and rare marble pods and ultramafite (Evans and Berti, 1986; Tabor et al., 1988).

In the study area, the Chiwaukum schist is semi-pelitic. It crops out as a blue-gray, fine to medium grained graphitic biotite-garnet schist. The characteristic mineral assemblage is quartz, oligoclase, biotite, garnet, epidote, chlorite, and graphite with a trace of sphene, rutile, muscovite, zircon and opaques.

Quartz layers, one to two cm thick, pinch and swell throughout the region parallel to a steeply dipping foliation. In thin section, the foliation is recognized by a preferred orientation of phyllosilicates, elongate quartz and feldspar, and graphite. Porphyroblasts have incorporated graphitic inclusions. One sample (174-45b) along the Napeequa contact contains staurolite (Fig 13).

Napeequa Migmatite

The Napeequa migmatite consists of a schist host pervaded by granitic dikes and sills. The schist includes fine to medium grained biotite-hornblende-garnet schist, biotite-muscovite-garnet schist, hornblende schist, quartzose-biotite schist, and amphibolite. The schist also contains rare marble layers and ultramafic pods.

The granitic sills and dikes are made up of a light-colored biotite-muscovite gneissic rock ranging in composition from tonalite to granodiorite. Dikes contain the assemblage plagioclase, quartz, K-feldspar, biotite, muscovite, garnet, and epidote. A moderate to strong foliation, recognized as aligned micas in outcrop, is defined by

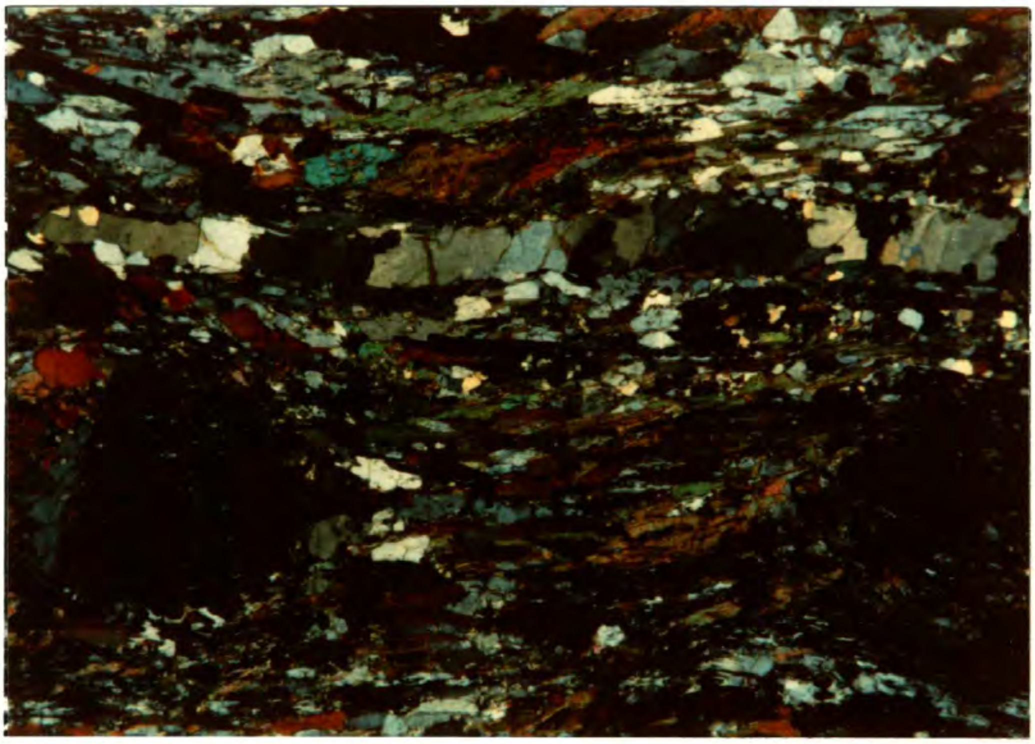

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Figure 13. Photomicrograph of graphitic garnet-schist of the Chiwaukum unit (specimen 174-13b). Section is cut normal to foliation and parallel to mineral lineations defined by aligned biotite. Extinct grains in lower half of the picture are garnet. Crossed nicols.

alignment of recrystallized elongate grains of quartz and feldspar, and subhedral muscovite and biotite. Sparse garnet is euhedral. Epidote grains are euhedral, average less than 0.5 mm, contain allanite cores, and are commonly found in biotite aggregates. The epidote is presumed to be a primary igneous mineral (Zen, 1988).

Gneissic layers pinch and swell. They range in thickness from a few centimeters to several meters, averaging 50 cm. For this report, the unit is delineated where the granitic rock makes up between approximately 20 and 90% of the migmatite. Where percent of the rock exceeds 90%, the rock is mapped as a plutonic body.

Unit contacts are gradational with the Napeequa unit and both the Downey Creek and the Bench Lake plutons. Schist layers resemble rocks of the Napeequa unit. The gneissic dikes can be traced into the Downey Creek and Bench Lake plutons. The migmatite unit is therefore interpreted to represent an injection zone of dikes into the Napeequa unit during emplacement of these plutons.

Cretaceous Plutons

A continuous northwest to southeast belt of tonalitic and dioritic plutons intrude metamorphic rocks in the study area. The plutons are described below in order of established or inferred ages from oldest to youngest; south to north. Mineral assemblages, rock classifications, and modes for each pluton are described in Ford et al. (1988). Chemical analyses, performed by Ralph Dawes at the University of

Washington, for the Downey Creek, Bench Lake, and Cyclone Lake plutons are given in appendix 2. Normalized SiO_2 Wt% range from 71.61 to 72.78. MgO/FeO vs SiO_2 normative field components suggest a calc-alkaline affinity indicative of a magmatic arc. U/Pb analysis of zircons from the Jordan Lake pluton is reported in Walker and Brown, 1991. Samples collected for geochronology from the Cyclone Lake, Bench Lake, and Downey Creek plutons for this report are presently awaiting analysis by Nick Walker.

Downey Creek granodiorite

The Downey Creek pluton is a light-colored, fine to medium grained muscovite-biotite granodiorite. This unit contains the igneous mineral assemblage plagioclase, microcline, quartz, muscovite, biotite, and garnet. Zircon, sphene, apatite, and opaques are accessory minerals and secondary chlorite and epidote are common. The percent mafics is 3-10.

Near Mule Lake, the granodiorite is homogeneous and crops out as sills and dikes grading into the Napeequa migmatite. In outcrop, a moderate foliation is recognized as aligned muscovite and biotite. In thin section, quartz and feldspars display subhedral to anhedral granular texture.

Some plagioclase grains display concentric zoning representing igneous texture. Plagioclase cores tend to be altered to anhedral grains of epidote. Chlorite commonly partially replaces biotite.

Mostly, however, quartz and feldspar are recrystallized into elongate subgrains and planar aggregates creating a mortar texture aligned with subhedral muscovite and biotite. Grain boundaries are commonly sutured (Fig 14). Sparse garnet is euhedral. Analyzed garnet in a sample from dike rock associated with the Downey Creek pluton (174-9b) is spessartine-rich (MnO content = 13.4 weight %, App 3).

Bench Lake tonalite

The Bench Lake pluton is a light-colored fine to medium grained muscovite-biotite tonalite. The rock contains the igneous mineral assemblage plagioclase, quartz, K-feldspar, biotite, muscovite, sphene, epidote, and hornblende. Zircon, apatite, and opaques are accessory minerals and chlorite and epidote are secondary. The percent mafics is 3-20. The unit was examined in two areas for this study: 1) the eastern portion of the pluton near Long Gone Lake, and 2) the southwestern portion of the pluton near Mt. Buckindy.

In the vicinity of Long Gone Lake, the tonalite is homogeneous and displays a moderate foliation defined by aligned biotite and muscovite. In thin section, the foliation is recognized by alignment of recrystallized elongate grains of quartz and feldspar, euhedral sphene grains up to 4 mm, and subhedral muscovite and biotite. Quartz and feldspar display anhedral granular texture with moderately sutured boundaries (Fig 15). Many euhedral epidote grains averaging 0.5 mm contain allanite cores and are usually found in biotite aggregates (Fig 16). The epidote is presumed to

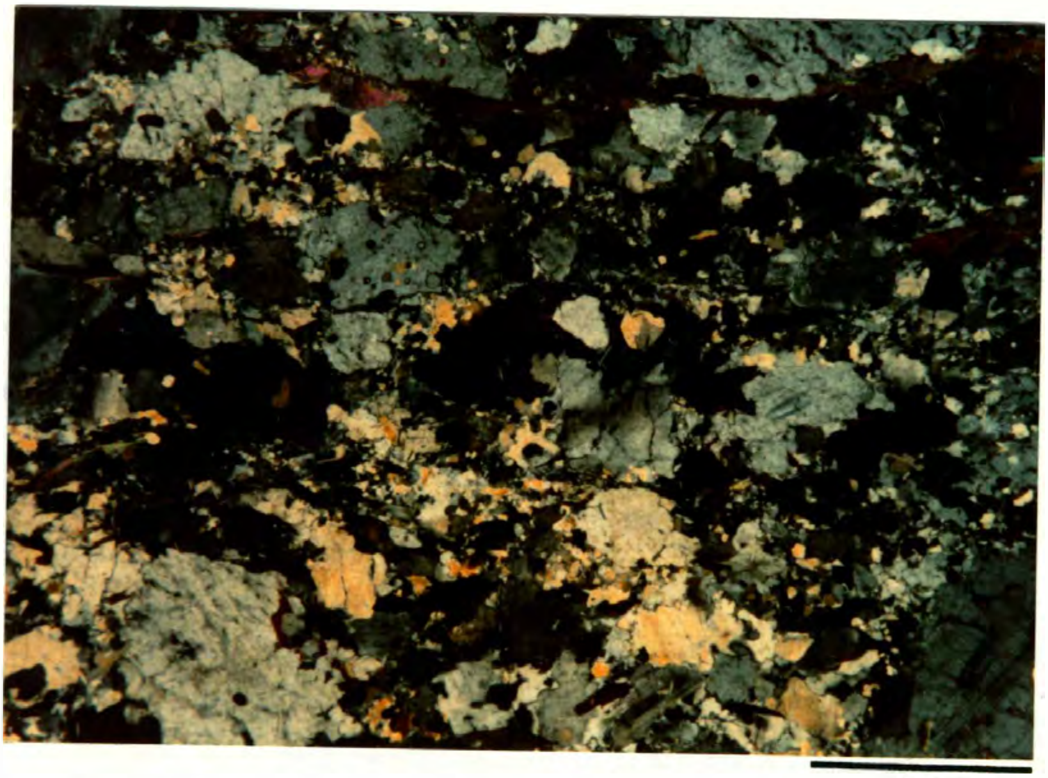


Figure 14. Photomicrograph of typical granodiorite of the Downey Creek pluton (specimen 174-2a). Quartz is highly undulose and, with plagioclase, displays mortar texture. Section is cut normal to foliation defined by aligned biotite, muscovite, and recrystallized quartz and plagioclase. Crossed nicols.

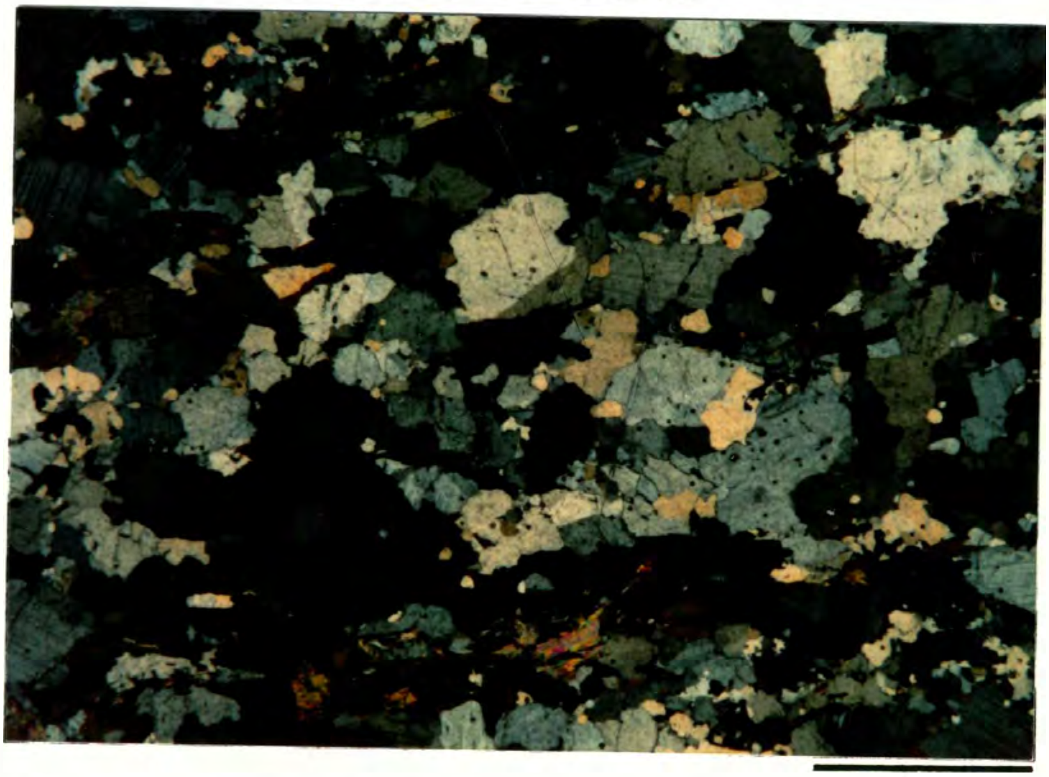
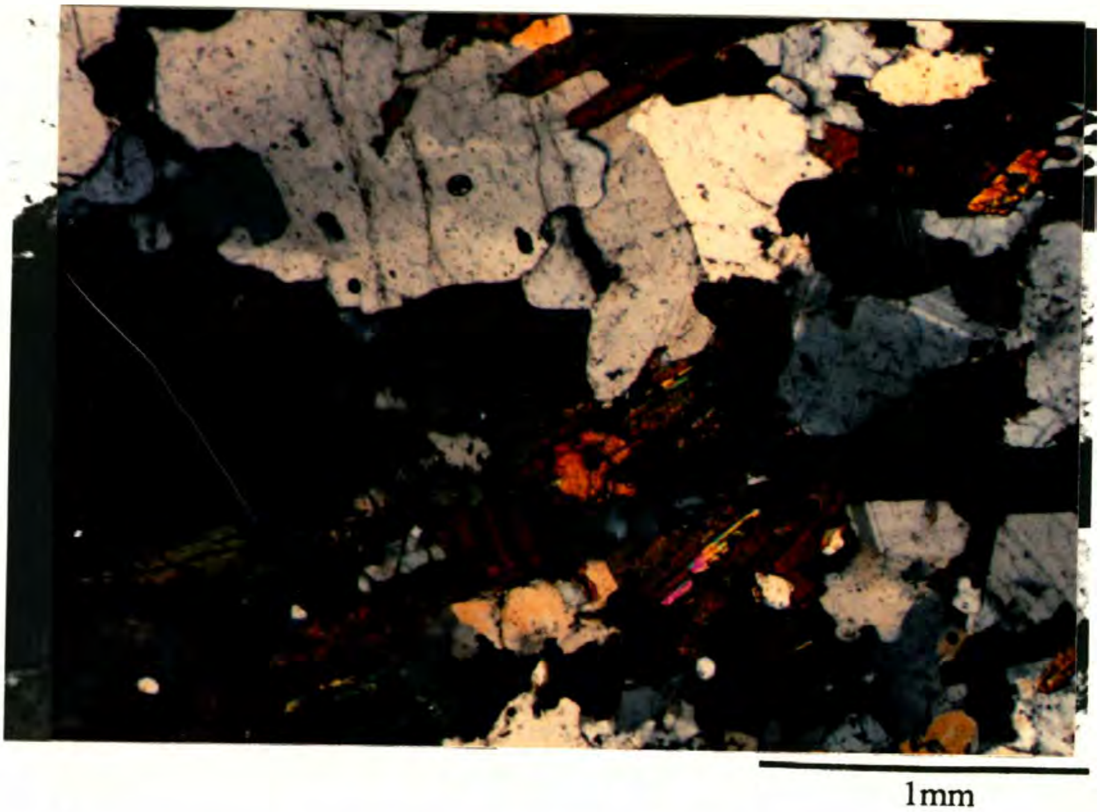


Figure 15. Photomicrograph of typical tonalite of the Bench Lake pluton (specimen 174-37a). Section is cut normal to foliation defined by aligned biotite, muscovite, and sphene. Crossed nicols.

A



B

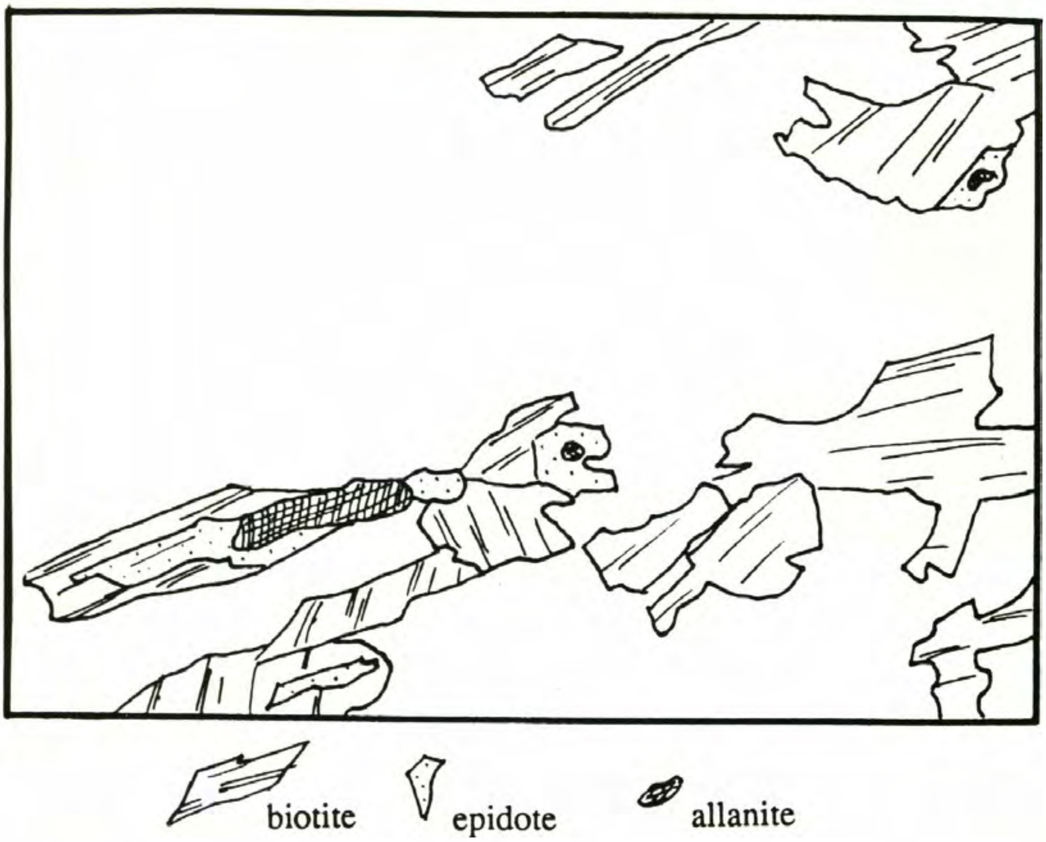


Figure 16. A) Photomicrograph of the Bench Lake tonalite showing euhedral magmatic epidote in contact with biotite (specimen 174-37a). B) Sketch of the photo showing epidote grains with allanite core. Crossed nicols.

be a primary igneous mineral due to its euhedral habit, common allanite cores, and association with magmatic plagioclase, biotite, and sphene (Zen, 1988).

Tonalite in the vicinity of Mt. Buckindy resembles tonalite elsewhere in the pluton except that locally it displays extensive metamorphic recrystallization. The rock has a penetrative iron oxide stain presumably dating from the injection of the nearby Tertiary Buckindy pluton. Though some samples display little alteration, plagioclase, K-feldspar, and undulose quartz in deformed samples are highly sutured and recrystallized creating a mortar texture. Biotite is anhedral and usually replaced by chlorite; sphene is embayed and partially replaced by opaque minerals; and some plagioclase displays alteration to epidote or white mica. Sparse hornblende is euhedral.

Cyclone Lake granodiorite

The Cyclone Lake pluton is a homogeneous light-colored fine to medium grained muscovite-biotite granodiorite. This unit contains the igneous assemblage plagioclase, K-feldspar, quartz, biotite, and muscovite. Zircon, epidote, apatite, and opaques are accessory minerals and chlorite and epidote are secondary. The percent mafics is 3-12.

In outcrop, a weak to moderate, subparallel alignment of micas defines a foliation. The rock becomes coarser grained and gneissic towards contact with the Jordan Lake pluton. In thin section, plagioclase, K-feldspar, and quartz display anhedral granular texture overprinted by sutured grain boundaries and mortar texture.

Coarse grained plagioclase augen with euhedral muscovite inclusions are wrapped by the foliation. Some perthitic textures are present and myrmekite is common. Biotite is subhedral to anhedral and can be found replaced by chlorite. Muscovite is found as euhedral grains clustered with biotite and as inclusions in plagioclase (Fig 17).

Jordan Lake tonalite

The Jordan Lake pluton is a light-colored, coarse grained biotite-hornblende tonalite. The rock contains the igneous assemblage quartz, plagioclase, K-feldspar, biotite, hornblende, and muscovite. Zircon, sphene, rutile, and apatite are accessory minerals and epidote is secondary. The percent mafics is 8-15.

The unit is largely undeformed and homogeneous in hand specimen and is easily recognized by its coarse grained appearance and biotite rich assemblage. In thin section, quartz grains are moderately undulose, plagioclase is typically partially altered to epidote or white mica, and biotite is kinked (Fig 18A). Coarse grained epidote is associated with plagioclase and lacks allanite cores and euhedral contact with biotite. This epidote is interpreted to be of metamorphic origin and not a primary igneous mineral.

On the ridge between Kindy and Found Creeks outcrop is well foliated, coarse grained granitic rock resembling the Jordan Lake pluton. This outcrop has previously been mapped as an appendage of the main pluton body (Tabor et al., 1988). Contacts were not followed into the main pluton body for this study and it is uncertain whether the rock is related to the undeformed pluton or an earlier intrusion resembling the

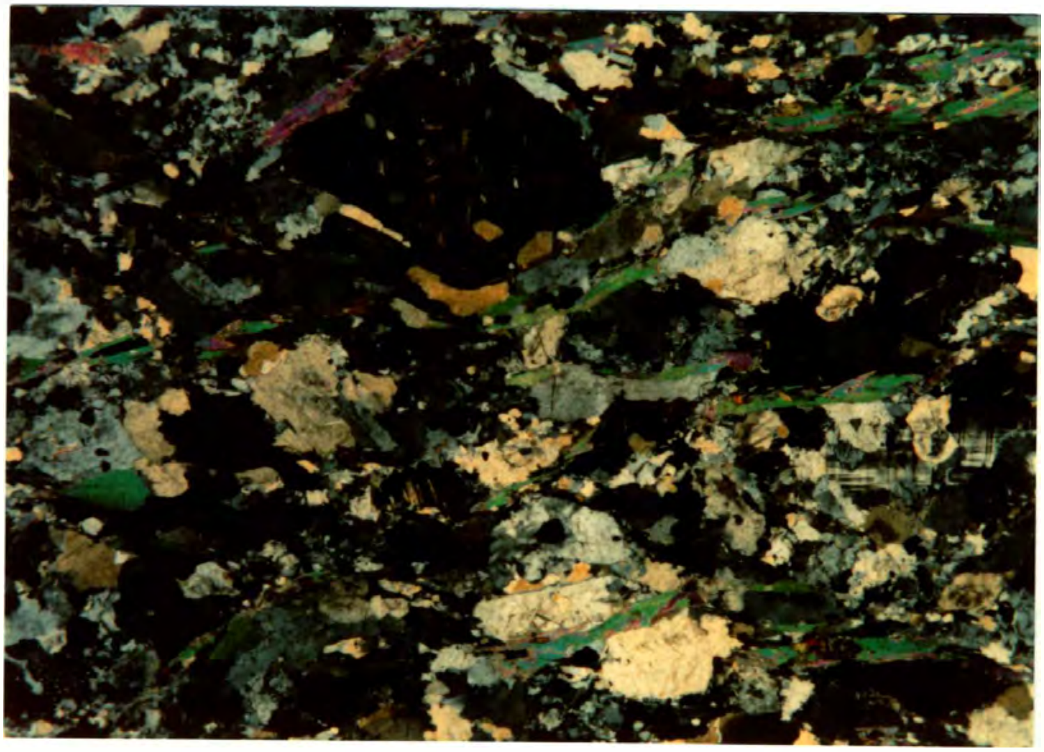


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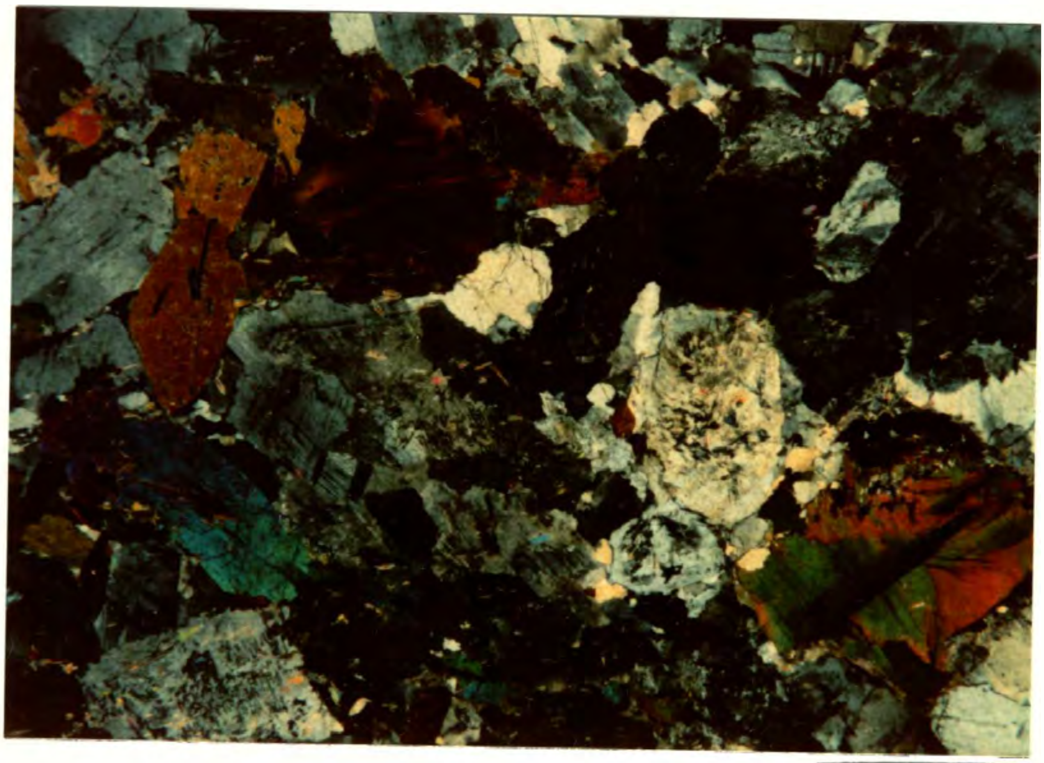
Figure 17. Photomicrograph of typical granodiorite of the Cyclone Lake pluton (specimen 174-107). Section is cut normal to foliation defined by aligned biotite, muscovite, and recrystallized, elongate quartz and plagioclase. Note the coarse plagioclase grain in upper center (extinct) with foliation wrapping around it. Crossed nicols.

A



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B

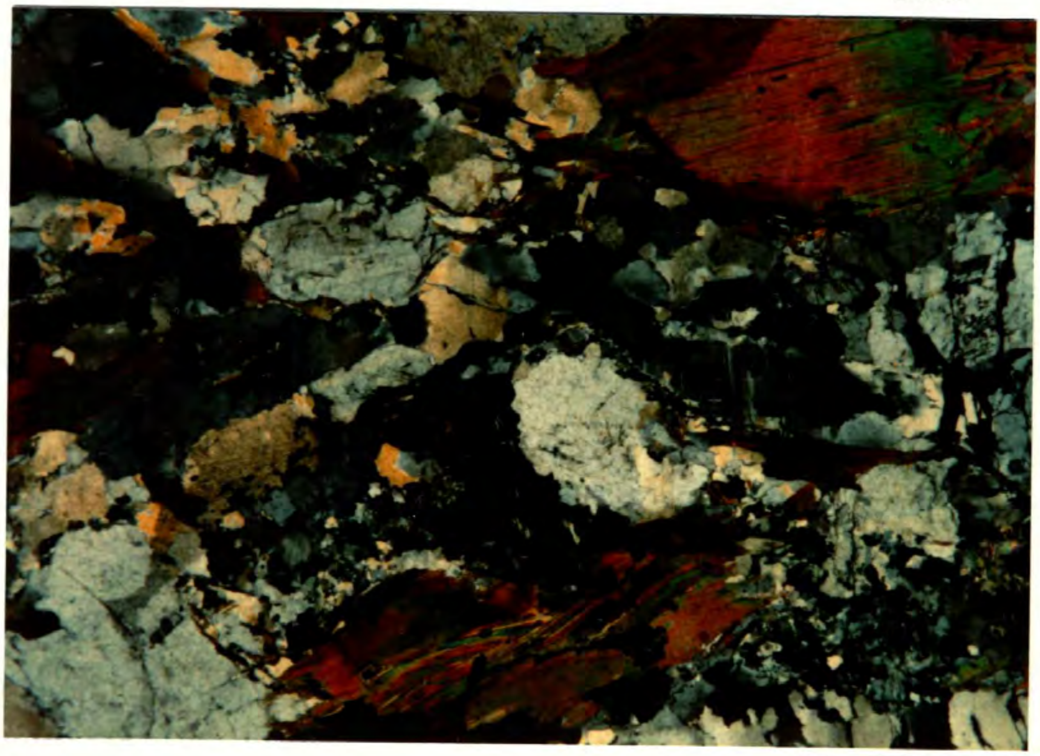

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Figure 18. Photomicrographs of the Jordan Lake pluton: A) typical undeformed granodiorite of the Jordan Lake pluton (specimen 174-122b). Note characteristic coarse grained texture, lack of foliation, kinked biotite, and alteration of plagioclase. B) Foliated granodiorite found on ridge between Kindy and Found Creeks. Both photos taken with crossed nicols.

Jordan Lake pluton. Foliation is concordant with the regional foliation in the nearby country rock and Cyclone Lake pluton. Biotite aligned with recrystallized and elongate quartz and feldspar grains define the foliation (Fig 18B).

Tertiary Units

Buckindy tonalite

Miocene tonalite and granodiorite porphyry is exposed as the Mount Buckindy pluton and as stocks within the Bench Lake tonalite, the Cyclone Lake granodiorite, and the Napeequa migmatite. This unit is on strike with and associated with the Cascade Pass dike. It is found mostly as a gray porphyritic biotite-hornblende tonalite to hornblende tonalite. A fine-grained subhedral granular groundmass surrounds euhedral to subhedral plagioclase, biotite, and hornblende. K-Ar analysis of hornblende and biotite give ages of 13.8 - 16.0 Ma (Tabor et al., 1988).

Breccia

Breccia is associated with the intrusion of the Buckindy tonalite into the Bench Lake pluton. This unit, exposed as spires and cliffs northwest of Mt. Buckindy, contains clasts of tonalite from 1 to 100 cm. in a vuggy quartz and iron oxide matrix.

It is also exposed near the contact of the Bench Lake pluton and the Napeequa migmatite north of Mt. Misch (peak 7401') as clasts of biotite schist and tonalite in a vuggy quartz matrix grading into porphyritic biotite-hornblende tonalite of the Mount Buckindy pluton.

METAMORPHISM

Introduction

The purpose of this section is to document the metamorphic gradients of the study area through the mapping of metamorphic zones and thermobarometry. In the Mt. Buckindy/Snowking region, mineral assemblages and thermobarometry indicate that Barrovian metamorphism increases from lower greenschist facies in the northwest to upper amphibolite facies in the south. Textures and barometry of Cretaceous plutons suggest that magma was emplaced during metamorphism.

Isograds and Metamorphic Zones

Introduction

Samples collected throughout the study area were examined by microscopy and microprobe analysis to ascertain characteristic mineral assemblages. A petrogenetic grid summarizing published estimated stability fields of index minerals and assemblages in the study area is given in figure 19. Metamorphic isograd maps are provided in figures 20 and 21 to show locations of samples used to delineate metamorphic zones and facies. Isograds are only approximated in some areas owing to lack of samples from areas of poor exposure, difficult access, or inappropriate mineralogy.

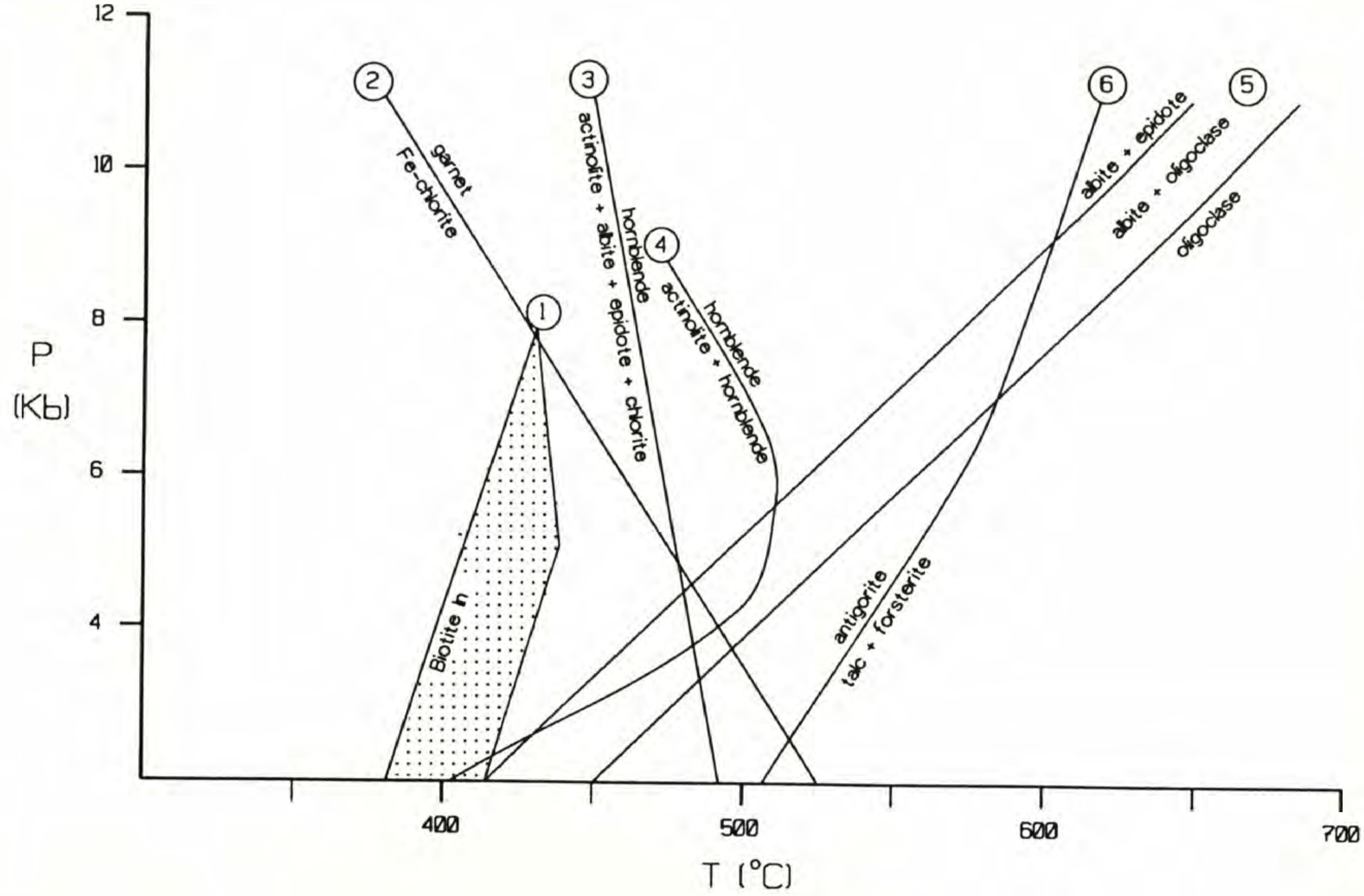


Figure 19. Petrogenetic grid showing estimated positions for reaction lines for metamorphic index minerals in the study area. Sources for the curves are: Yardley (1989) (1); Brown (1978) (2,3); Maruyama (1983a) (4, 5); and Trommsdorf and Evans (1972) (6).

Greenschist Facies

Greenschist facies metamorphism was previously reported to the north of this study in the vicinity of the Cascade River, where rocks of the Marblemount meta-quartz diorite and the Cascade River unit, west of the Entiat fault, display the characteristic mineral assemblages of this facies (Bryant, 1955; Misch, 1966; Dragovich, 1989; and Cary, 1990). Barometric evidence, utilizing the crossite component (*Na M4*) of actinolite as proposed by Brown (1977), suggests pressures of 3-4 Kb (Cary, 1990).

Chlorite zone - A chlorite zone is recognized by the complete absence of biotite in the northwest corner and north of the field area in the Marblemount meta-quartz diorite and the phyllite of the Napeequa unit (Fig 20). Characteristic mineral assemblages are quartz + albite + chlorite + muscovite ± calcite ± graphite ± opaques.

Biotite zone - The biotite isograd is recognized by the first appearance of metamorphic biotite (1; Fig 19). The isograd appears to crosscut the contact between the phyllite of the Napeequa unit and the Marblemount meta-quartz diorite (Fig 20A). A large percentage of samples in the biotite zone lack biotite, thus location of the isograd is controlled by rock composition.

Garnet zone - The garnet isograd is recognized by the first appearance of garnet (2; Fig 19). A garnet isograd is delineated within the quartz-biotite schist of

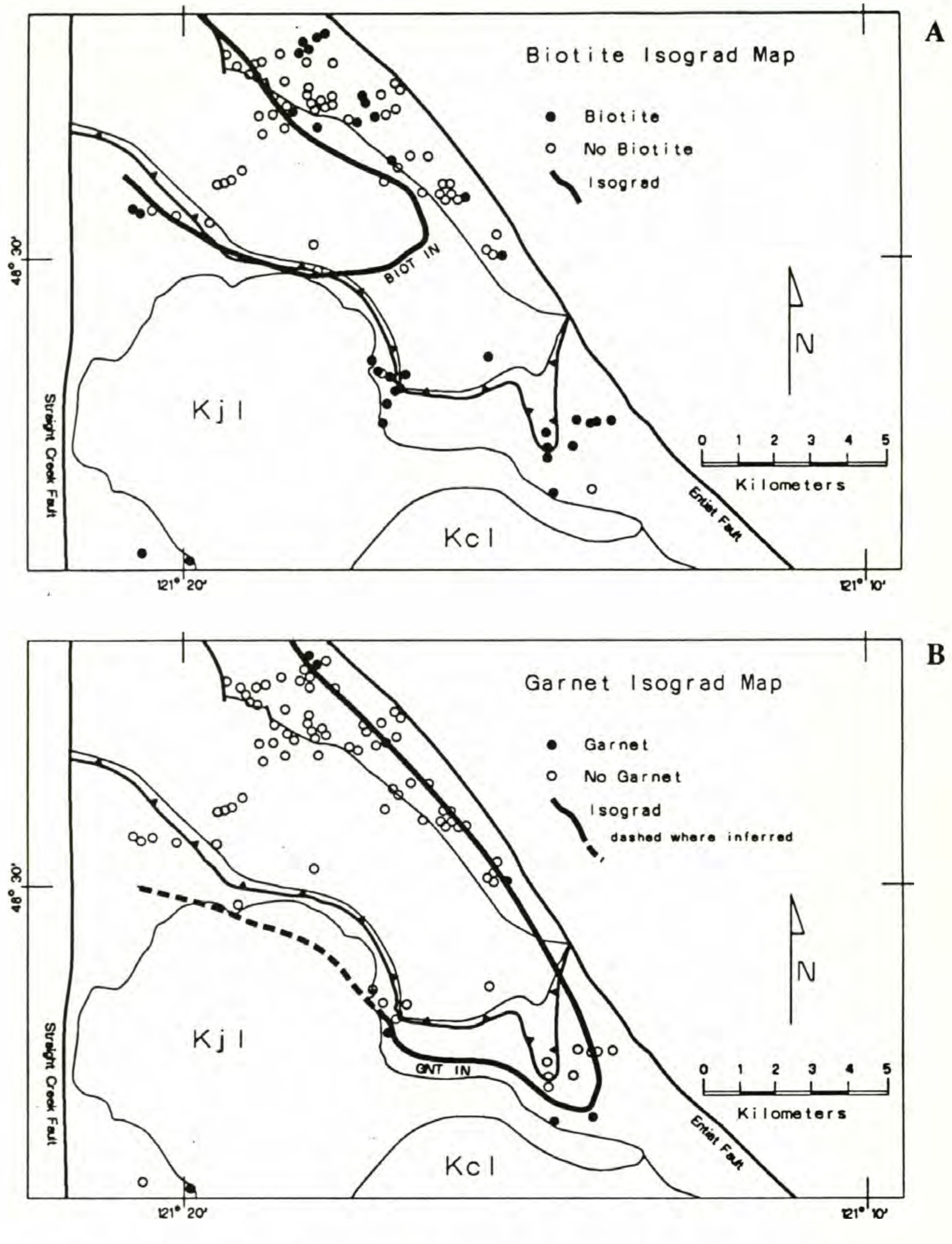


Figure 20. Biotite (A) and garnet (B) isograds delineated by data obtained from Dragovich (1989), Cary (1990), Brown (unpublished), and this study. Geologic unit symbols are shown in figure 5.

the Napeequa unit south of contact with the Marblemount meta-quartz diorite (Fig 20B). Rock composition plays a significant role in distribution of the garnet.

__Actinolite-Hornblende isograd__ - An actinolite-hornblende isograd is recognized where actinolite (Si > 7.25) is replaced by hornblende (Si < 7.25). Brown (1978) suggests that the reaction albite + epidote + chlorite + actinolite = hornblende occurs within the greenschist facies at temperatures around 475 °C for pressures above 4 Kb (3; Fig 19).

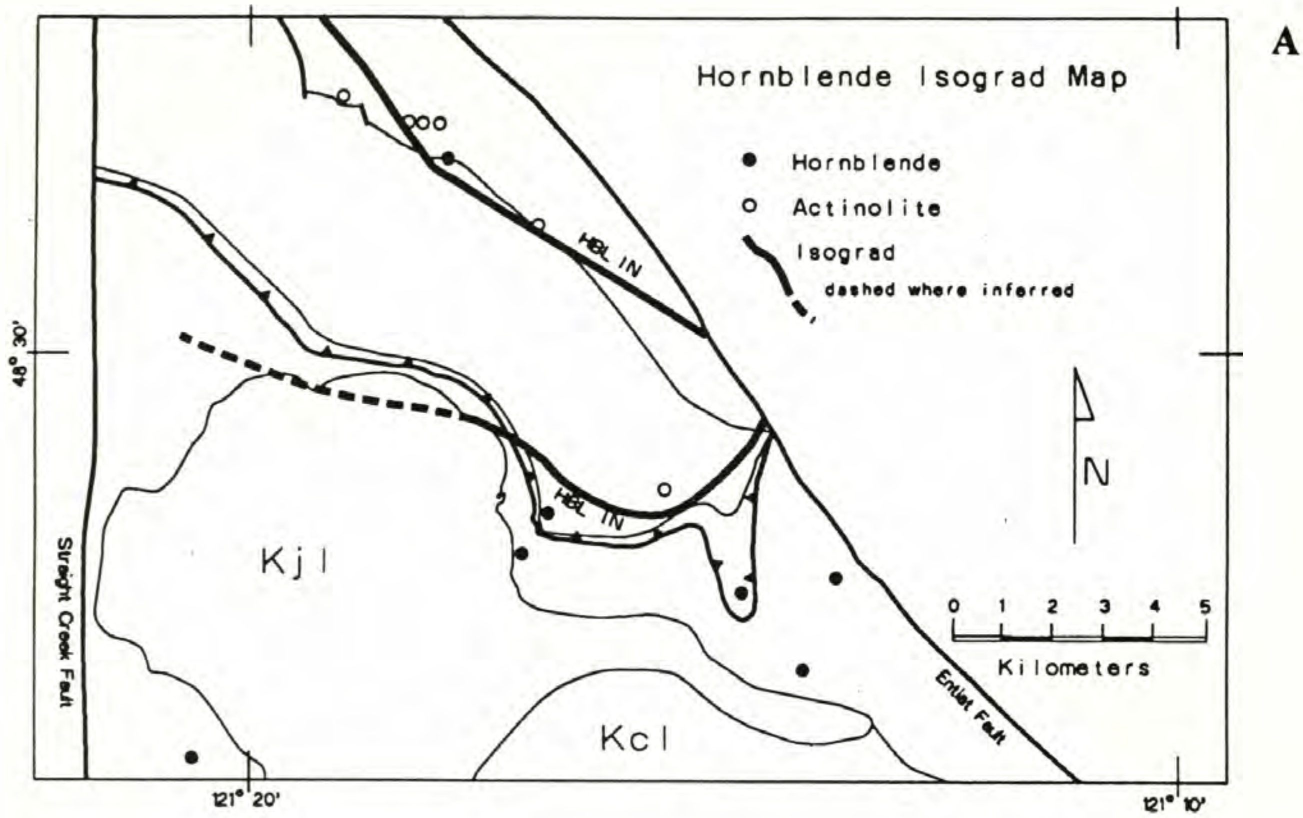
Maruyama et al. (1983a) suggests a compositional range of amphiboles from actinolite to actinolite + hornblende to hornblende in progressive metamorphism from greenschist to amphibolite facies. A compositional gap, recognized by the coexistence of actinolite and hornblende, marks the greenschist to amphibolite facies transition (4; Fig 19). According to Maruyama et al. (1983a), any absence of the compositional gap is attributed to low FeO/MgO whole rock compositions. In the study area, no such gap is recognized, although the isograd is bracketed by few samples. This isograd is found near the southern contact of the Marblemount unit (Fig 21A).

Greenschist-Amphibolite Facies Transition

__Albite-Oligoclase isograd__ - The boundary between the greenschist and amphibolite facies has been traditionally marked by the transition from albite to oligoclase (Turner, 1981). Coexistence of albite and oligoclase, and the lack of plagioclase with the approximate range of compositions An $_{5\text{-}20}$, in progressive metamorphism within the transition zone, is due to a peristerite immiscibility gap (Evans, 1964; Maruyama et al., 1983a,b)(5; Fig 19).

Microprobe analysis of rocks in the northern part of the study area reveal one sample with anorthite composition An $_1$ (164-315a), one sample with coexisting An $_8$ and An $_{19}$ (164-410a), and four samples with anorthite composition greater than An $_{25}$ (174- 114b,118a; 164- 73c,78). Based on these data, an albite-oligoclase isograd can be delineated near the southern contact of the Marblemount unit. The isograd crosscuts the contact between schist of the Napeequa unit and the Marblemount meta-quartz diorite (Fig 22B).

Although there are not enough samples to eliminate the possibility that the isograd is located within the Marblemount unit, a crosscutting isograd is delineated based on the following lines of evidence. The Marblemount unit increases in grade from chlorite zone greenschist facies in the northwest to amphibolite facies in the south. The Napeequa unit also increases in grade from chlorite zone phyllites of the greenschist facies in the northwest to schists of the amphibolite facies along the southern contact with the Marblemount unit. This transition from greenschist to amphibolite facies is consistent between the two units and therefore most likely formed simultaneously, i.e., after or during the juxtaposition of the two units.



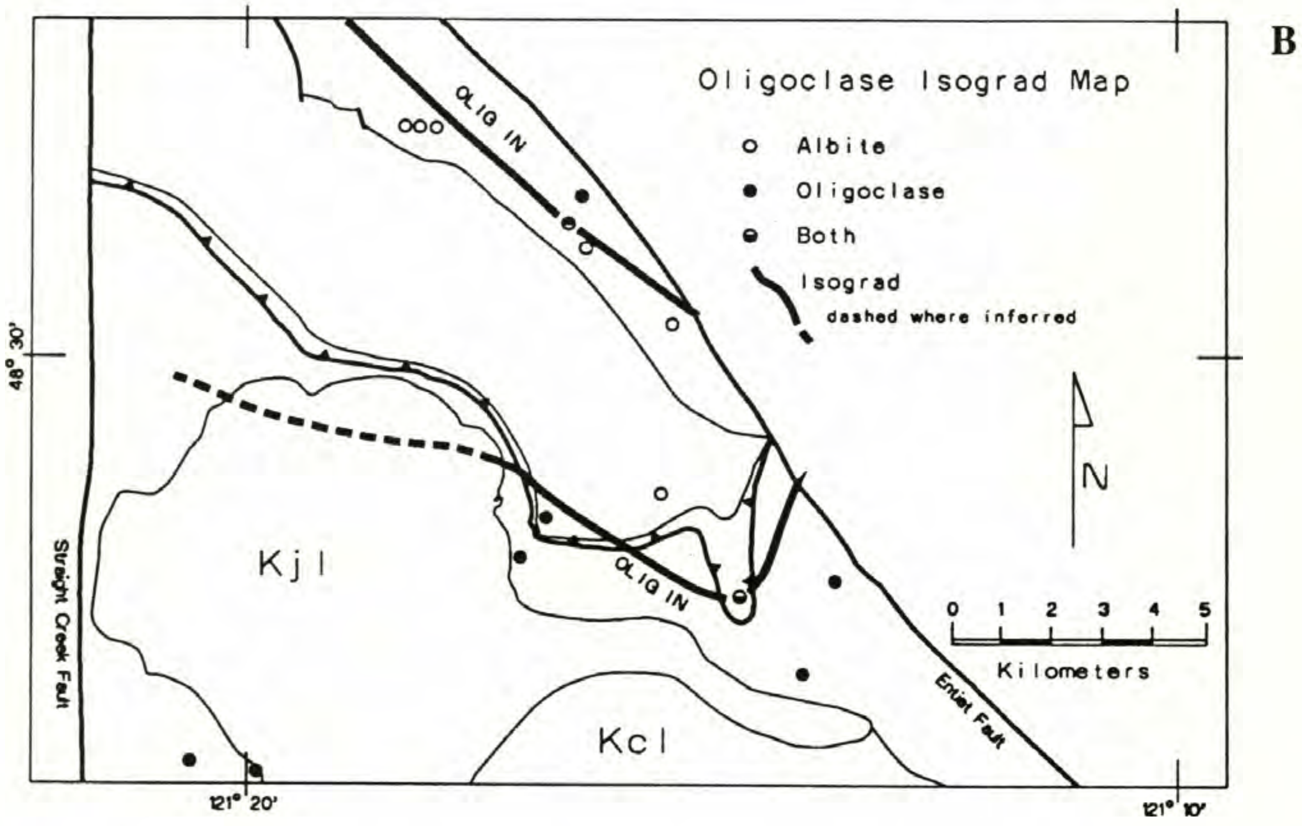


Figure 21. Hornblende (A) and oligoclase (B) isograds delineated by data obtained from Dragovich (1989), Cary (1990), Brown (unpublished), and this study. Geologic unit symbols are shown in figure 5.

Amphibolite Facies

Amphibolite facies metamorphism has previously been recognized by workers in the southern part of the field area. Bryant (1955), Tabor (1988), and Bittenbender (1991) have reported that rocks of the Chiwaukum schist, to the south and southwest of the study area, contain assemblages indicative of the mid to upper amphibolite facies. The schists and amphibolites of the Napeequa unit are also in the amphibolite facies, as indicated by hornblende and oligoclase occurrences, but aluminous index minerals are lacking due to inappropriate bulk composition.

Staurolite zone - In this study, only one occurrence of staurolite-bearing schist has been recognized in the more pelitic rock of the Chiwaukum schist. Sample 174-45b contains the assemblage garnet + chlorite + biotite + staurolite + muscovite + quartz (Fig 22A). The coexistence of chlorite, garnet, biotite, and staurolite suggests that staurolite formed from the discontinuous reaction garnet + muscovite + chlorite $\rightarrow$ staurolite + biotite + quartz (Albee, 1965; Yardley, 1989). An AFM projection, based on microprobe analysis of the sample, shows how a tie-line flip from garnet-chlorite to staurolite-biotite occurs at this reaction (Fig 22B). The coexistence of all four minerals possibly indicates that the rock was metamorphosed at or near the reaction line (Carmichael, 1970).

Talc + Forsterite stability - Ultramafic rocks in the southern (high grade) region of the study area are metaperidotites containing the assemblage forsterite, talc,

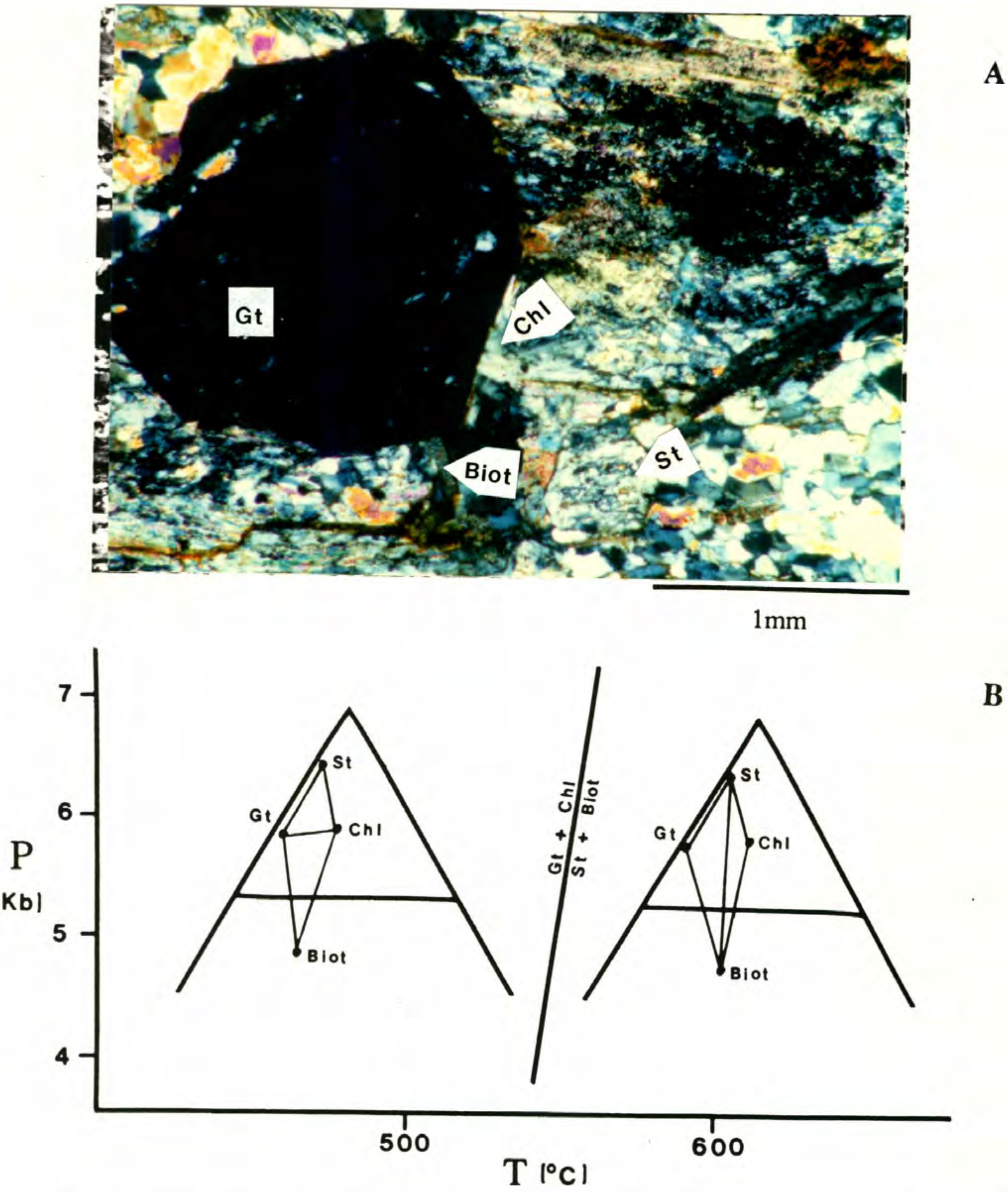


Figure 22. Phase petrology of garnet-staurolite schist. A) Photomicrograph of garnet-staurolite schist of the Chiwaukum unit displaying the assemblage garnet, chlorite, muscovite, staurolite, and biotite (specimen 174-45b). B) Reaction line (approximate P-T location) at the staurolite-biotite isograd with AFM projections showing a tie-line flip. At the reaction, garnet-chlorite stability is replaced by staurolite-biotite stability. The specimen, displaying all four minerals in apparent equilibrium, probably reflects metamorphism at or near the reaction line.

chlorite, and opaques with retrogressive antigorite. The coexisting forsterite and talc can be derived from lower grade serpentine by the reaction antigorite $\rightarrow$ olivine + talc + H_2O (Trommsdorf and Evans, 1972). This reaction has a steep positive slope in P-T space and occurs in the middle amphibolite facies at temperatures between 500 and 600 °C (6; Fig 19). Enstatite and anthophyllite are formed from the continuous reaction of olivine and talc at higher temperatures. The absence of these minerals indicates that temperatures did not exceed 600-800 °C, a finding compatible with thermobarometric results (below).

Thermobarometry

Metamorphic pressures and temperatures were determined in this study from compositions of coexisting minerals using a variety of calibrations based on mineral equilibria. Appropriate equilibrium assemblages utilized are: 1) garnet + biotite + muscovite + plagioclase, or 2) garnet + hornblende + plagioclase. The depth of crystallization of the plutons is based on the total Al content in igneous hornblende.

Microprobe analyses were carried out by E.H. Brown using facilities at the University of Washington. Samples selected display equilibrium textures. Minerals are preferably idioblastic, unaltered, and in close proximity to one another. Garnet and plagioclase were usually checked for zoning with rim analyses of similar compositions averaged together. The mineral formulas obtained from the microprobe data are listed in appendix 3 for each sample. Sample localities are shown on the geologic map (plate 1).

Thermometry

Calibrations for thermometers are based on the following reactions:

1) *GABIOT* Fe and Mg partitioning between biotite and garnet (calibration of Berman, 1991).

2) *GAHB* Fe-pargasite + pyrope = pargasite + almandine (calibration of Graham and Powell, 1984).

Barometry

Calibrations for barometry are based on the following reactions:

1) *GAMICA-Mg* pyrope + grossular + muscovite = plagioclase + phlogopite (calibration of Berman, 1991).

2) *GAMICA-Fe* almandine + grossular + muscovite = plagioclase + annite (calibration of Berman, 1991).

3) *HBGAPL-Mg* anorthite + tremolite = grossular + pyrope + tschermakite + quartz (calibration of Kohn and Spear, 1990).

4) *HBGAPL-Fe* anorthite + Fe-actinolite = grossular + almandine + Fe-tschermakite + quartz (calibration of Kohn and Spear, 1990).

Igneous barometry

A barometer based on the total Al content of magmatic hornblende (Al_T) for calc-alkaline plutons has been applied using the calibrations of Hollister et al. (1987) and Schmidt (1992).

The calibration of Hollister et al. (1987) is based on an empirical calibration for plutons with the assemblage plagioclase, quartz, hornblende, biotite, orthoclase, magnetite, and sphene. The average compositions of hornblende rims from plutons are correlated with pressures of intrusion independently derived from the metamorphic country rock. Pressures ranging from 2 to 8 Kb, linearly fit to the Al_T of hornblende, create a curve that is similar to that proposed by Hammarstrom and Zen (1986), but with a smaller error of ± 1 Kb. Pressure values calculated to be below 2 Kb are considered to be inaccurate due to a large temperature effect on Al_T in hornblende during final crystallization.

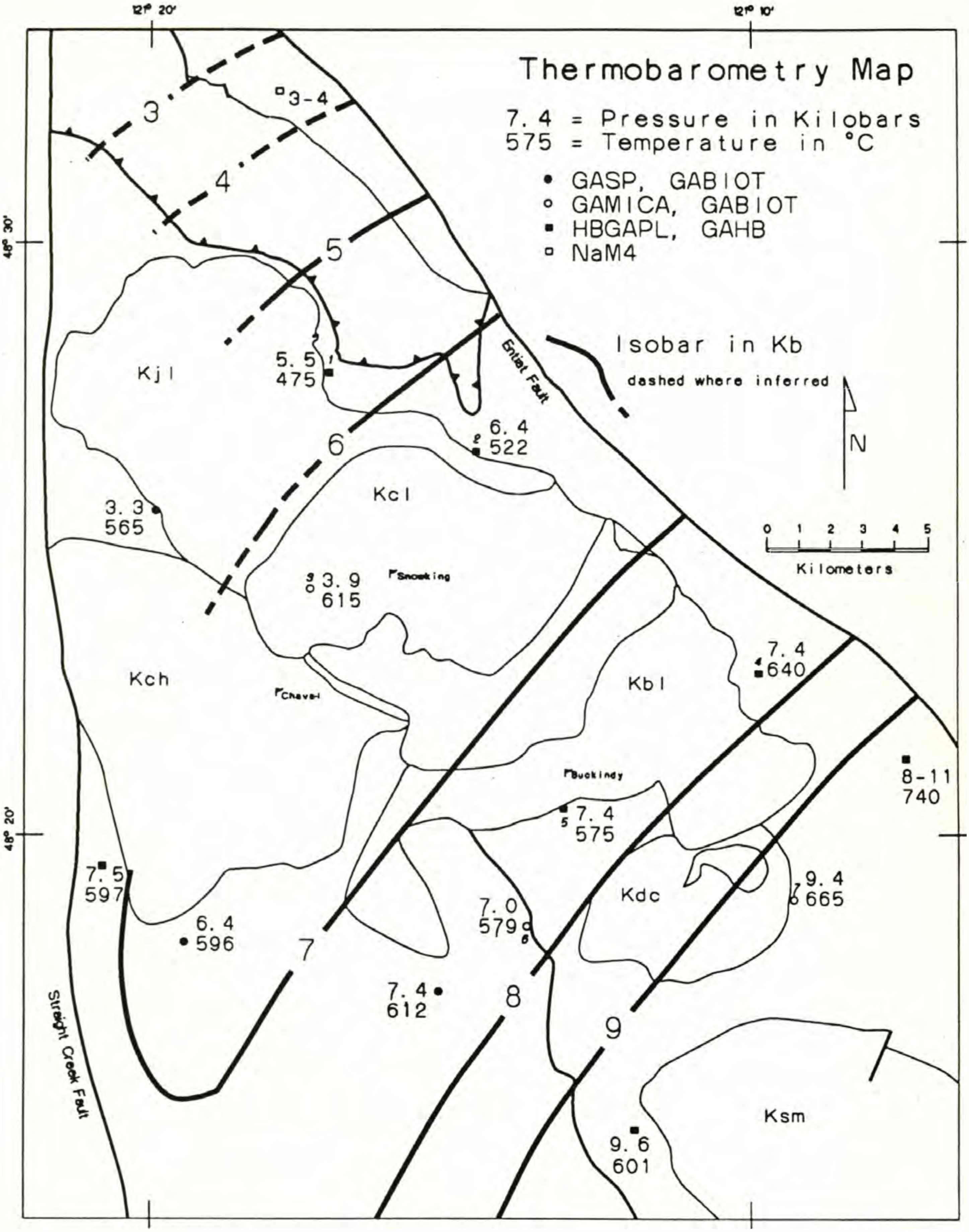
The hornblende barometer of Schmidt (1992) is based on an experimental calibration for the assemblage hornblende, biotite, plagioclase, orthoclase, quartz, sphene, and Fe-Ti oxide. Natural samples of calc-alkaline volcanic and plutonic rock were equilibrated at pressures ranging from 2.5 to 13 Kb at 700-655 °C. The barometer is estimated to have an error of ± 0.6 Kb.

Results

Metamorphic pressures and temperatures - The results of thermobarometry on country rock in the study area are given in table 1. These results are combined with data from previous work adjacent to the study area and plotted on a regional map in figure 23. Sample localities of specimens analyzed are numbered 1-7. Isobars are drawn through the data points.

Figure 23. Thermobarometric map showing pressures and temperatures obtained from the country rock data and the delineated isobars. Sample localities taken from this study are numbered 1-7 (table 1). Calibrations used include: *GABIOT* (Berman, 1991); *GAHB* (Graham and Powell, 1984); *GAMICA* (Berman, 1991); and *HBGAPL* (Kohn and Spear, 1990). Calibrations used for barometry by other workers include: *GASP*- garnet + alumino-silicate + quartz $\rightarrow$ anorthite (Berman, 1991); and *Na M4*- crossite component of actinolite (Brown, 1977).

Other workers' data include that of: Cary (1990) from the Cascade River unit near the northeast contact of the Marblemount unit; Bittenbender (1991) from the Chiwaukum schist south of the Chaval pluton; Dougan (1992) from the Napeequa migmatite 3 Km east of the Bench Lake pluton; and Brown (unpublished) from the Napeequa schist west of the Sulphur Mt. pluton and southwest of the Jordan Lake pluton, and from the Chiwaukum schist west of the Chaval pluton. Geologic unit symbols are shown in figure 5.



Thermobarometry Map
7.4 = Pressure in Kilobars
575 = Temperature in °C
GASP, GABIOT
GAMICA, GABIOT
HBGAPL, GAHB
NaM4
Isobar in Kb
dashed where inferred
N
Kilometers
Entiat Fault
Straight Creek Fault
Kjl
Kcl
Kch
Kbl
Kdc
Ksm
3-4
5.5
475
6.4
522
3.3
565
3.9
615
7.4
640
8-11
740
7.4
575
7.5
597
6.4
596
7.0
579
9.4
665
7.4
612
9.6
601

Table 1. Thermobarometric results for country rock.

#	specimen	*GABIOT* T (°C)	*GAMICA* P (Kb)	*GAHB* T (°C)	*HBGAPL* P (Kb)
1	174-118a			575	5.5
2	164-73c	522	6.4		
3	174-33a	615	3.9		
4	174-36c			640	7.4
5	174-24			575	7.4
6	174-45b	579	7.0		
7	174-8a	665	9.4		

All of the metamorphic rocks analyzed appear to have reached equilibrium at peak metamorphic conditions, with two possible exceptions. A garnet-staurolite schist collected by Edwin H. Brown near the southwest margin of the Jordan Lake pluton (not listed in table 1) displays post-tectonic textures for garnet and staurolite. The equilibrium assemblage is probably reset by the late-stage or post-tectonic intrusion of the Jordan Lake pluton. Pressures and temperatures obtained for this sample are interpreted to reflect conditions at the time of emplacement. Sample 174-33a is a garnet-mica schist obtained from a screen within the Cyclone Lake pluton. The equilibrium assemblage is possibly reset by the Cyclone Lake pluton as recognized by high temperature and low pressure results. The equilibrium is assumed to reflect conditions at the time of emplacement, suggesting that the Cyclone Lake pluton is younger than the peak metamorphism in the area (see section on timing of Cretaceous plutonism and metamorphism).

Pressures range from 3 to 4 Kb in the northwest to over 9 Kb in the southeast. Isobars, plotted by extrapolation between data points, are well constrained in the southern high pressure region. The isobaric trends are orogen-normal. The gradient indicates that the loading material was thickest in the southeast. In the northern region, the isobars are poorly constrained and drawn parallel to those in the south. Low pressures in this region are indicated by *Na M4* barometry reported by Cary (1990) and are also supported by mineral assemblages of the Barrovian metamorphism. However, the exact location and trend of the low pressure isobars is uncertain. Their orientation could be affected by metamorphic events in adjacent areas or by the intrusion of late-stage to post-tectonic plutons in the area.

Depth of pluton crystallization - The results of pluton barometry are given in table 2; pressures from the calibration of Schmidt (1992) are plotted on the map of figure 24. Sample localities of specimens analyzed are numbered 8-14.

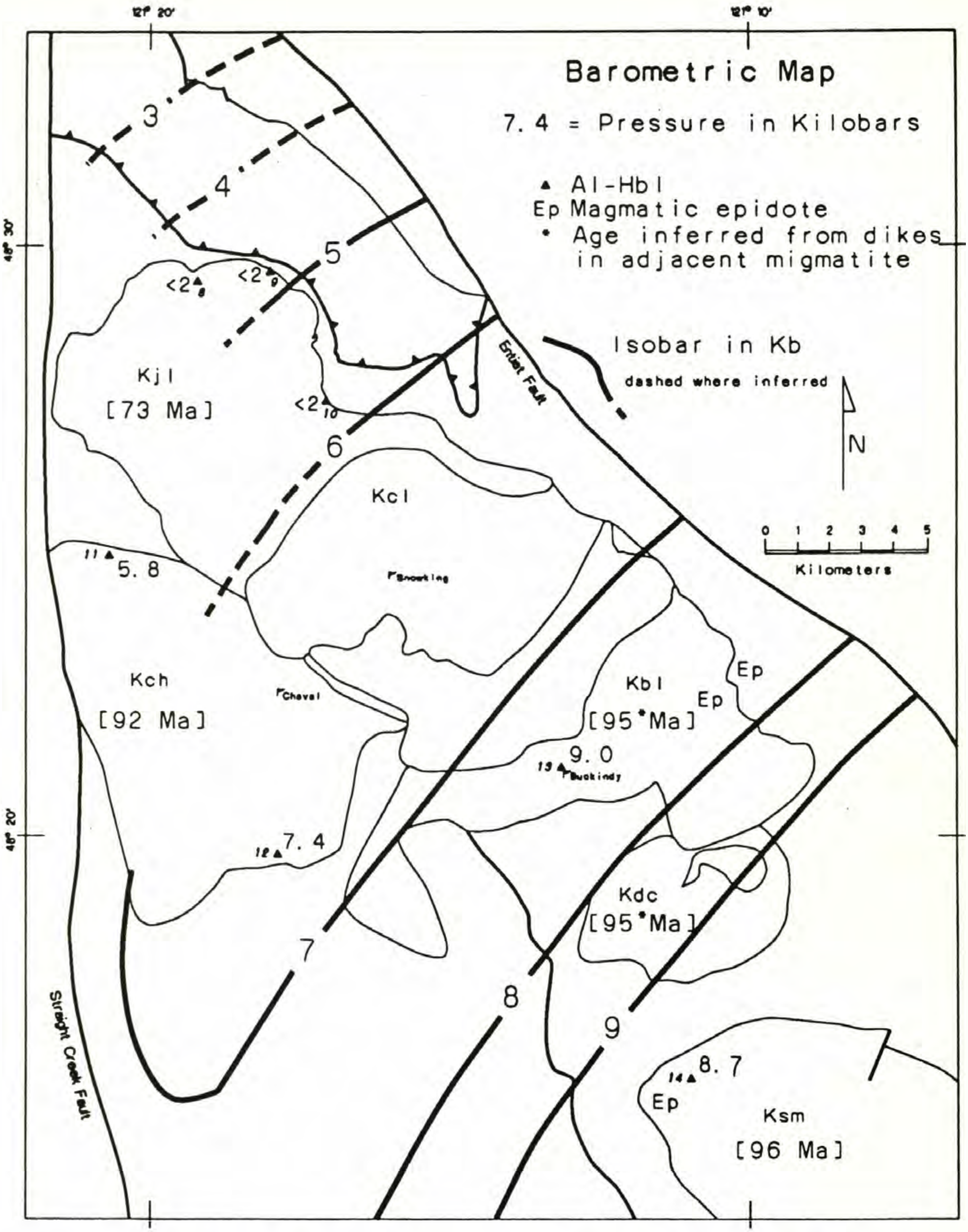


Figure 24. Barometric map showing crystallization pressures of the plutons and isobars delineated from country rock data. Sample localities are numbered 8-14 (table 2). * Age inferred to be that of dikes in adjacent migmatite (Walker pers. comm.). † Age from Walker and Brown, 1991. Geologic unit symbols are shown in figure 5.

Table 2. Barometric results for plutons.

#	specimen	P	Total Al weight %	Calibration (Kb) 1	2	Ref
8	164-20	JO	0.75	< 2	< 2	2
9	174-130	JO	0.91	< 2	< 2	1
10	174-122a	JO	0.99	< 2	< 2	1
11	164-35	CH	1.85	5.7	5.8	2
12	OHM-66	CH	2.18	7.5	7.4	3
13	174-49	BL	2.53	9.5	9.0	1
14	174-RH	SM	2.47	9.2	8.7	1

Plutons analyzed (P) are: JO = Jordan Lake; CH = Chaval; BL = Bench Lake; and SM = Sulphur Mt. Calibrations are: 1) Hollister et al., 1987; and 2) Schmidt, 1992. References for mineral data (Ref) are: 1) this study; 2) Brown (unpublished); and 3) Bittenbender (1991).

Depth of pluton emplacement varies in the region. Plutons with magmatic hornblende and appropriate buffering assemblages have a range of Al_T in hornblende that indicates pressures ranging from less than 2 Kb in the northwest to greater than 8 Kb in the south. Evidence constraining the depth of crystallization for the plutons based on barometry and mineral assemblages are listed below from oldest to youngest.

The 96 Ma Sulphur Mt. pluton contains high Al_T hornblende yielding pressures of 8.7 ±0.6 and 9.2 ±1 Kb, depending on the calibration used. The presence of magmatic epidote in the pluton also supports pressures greater than 6 Kb (Hammarstrom and Zen, 1986). The Bench Lake pluton contains high Al_T hornblende yielding pressures of 9.0 ±0.6 and 9.5 ±1 Kb. This is also supported by the presence of magmatic epidote. The 92 Ma Chaval pluton contains moderate Al_T hornblende yielding pressures of 7.4 ±0.6 and 7.5 ±1 Kb in the south, and 5.8 ±0.6 and 5.7 ±1 Kb in the north. The 73 Ma undeformed Jordan Lake pluton contains hornblende with a low Al_T yielding pressures less than 2 Kb. Since pluton barometry pressures of less than 2 Kb are deemed inaccurate due to temperature effects on Al^T of hornblende, then it is uncertain whether these results reflect crystallization depth or were affected by the buffering of other Al-bearing minerals in the assemblage.

Retrograde Metamorphism

In the Napeequa unit, retrograde metamorphism of schist is displayed rarely by the growth of chlorite crosscutting the fabric and by the occasional alteration of biotite to chlorite. Serpentinites also display retrograde metamorphism from the replacement of metamorphic forsterite with antigorite.

Gneissic Marblemount meta-quartz diorite displays retrograde actinolite needles splaying across the fabric (164-410a)(Fig 12).

Summary

The study of metamorphic mineral assemblages and thermobarometric analysis in the study area has led to the following conclusions. 1) A greenschist to amphibolite facies progression can be delineated. 2) Isograds appear to crosscut the Napeequa-Marblemount contact. Therefore, the Marblemount meta-quartz diorite was in place relative to the Napeequa unit before or during peak metamorphism in the region. 3) A strong baric gradient is orogen-normal and increases from northwest to southeast. Over an area of approximately 20 Km the pressures increase from 3-4 Kb to over 9.0 Kb. 4) Emplacement of plutons in the southern region appears to be at great depths in the range of pressures established for the surrounding country rock. By 73 Ma the metamorphic event had ceased and pressures indicate uplift in the northwest.

TIMING OF CRETACEOUS PLUTONISM AND METAMORPHISM

This section combines criteria of micro- and meso-scopic structures with metamorphic textural evidence to determine the time of emplacement of Cretaceous plutons relative to the metamorphic deformation. Known and inferred absolute ages of plutons are then used to constrain the timing of peak metamorphism.

Relative Timing of Plutonism With Respect to Regional Metamorphic Deformation

The Cretaceous plutons in the study area have several features in common: 1) contact aureoles appear to be absent except for the youngest, 73 Ma Jordan Lake pluton; 2) regional fabric is not significantly displaced by intrusion; 3) magmatic flow fabrics are absent or possibly obscured by later deformation; and 4) all plutons display some solid-state deformation. Listed below are characteristics recognized for each pluton studied pertaining to the relative timing of emplacement.

Southern Plutons

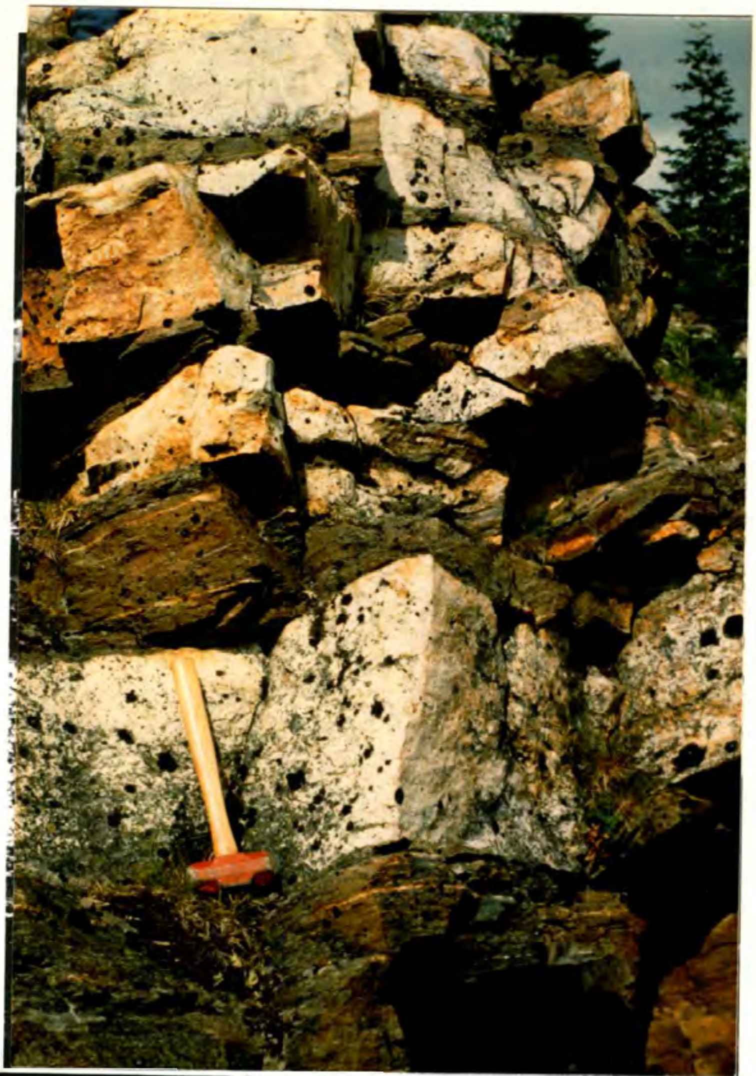
Downey Creek granodiorite - The Downey Creek pluton near Mule lake is composed of large sills and dikes that are aligned with the regional foliation and appear to be closely associated with the Napeequa migmatite. The igneous rock displays a moderate to strong solid-state deformational fabric that also is aligned with the regional foliation. Porphyroblasts in the country rock define the foliation and are interpreted to be syn-kinematic. Dikes in the Napeequa migmatite, near the pluton contact, are aligned with the foliation on a regional scale. On outcrop scale, the dikes contain a solid-state foliation parallel to the regional foliation and also crosscut the regional foliation (Fig 25).

Mineralogic evidence pertaining to the depth of crystallization of the pluton is lacking. The rock is highly-recrystallized, obscuring any magmatic textures such as those used to recognize magmatic epidote. Also, hornblende is absent from the mineral assemblage.

Bench Lake tonalite - The Bench Lake pluton displays moderate solid-state deformation related to the regional metamorphic deformation. The pluton also displays mineralogic evidence for emplacement at depths equal to those reached during peak metamorphism.

On the southwest-trending ridges approaching the eastern gradational contact of the pluton, near Long Gone Lake, dikes appear to originate from the pluton (Fig 26). The dikes dip towards the main pluton body, concordant with the regional foliation, and become larger and more abundant approaching the pluton. Comparison of mineral assemblages and textures provide further evidence that the dikes are associated with the Bench Lake pluton. In hand sample, the dikes resemble tonalite of the Bench Lake pluton; both are fine to medium grained with abundant biotite and recrystallized quartz and feldspar defining a solid-state foliation. Also, dike rock and nearby

A



B

Figure 25. A) Dikes in the Napeequa migmatite, closely associated with the Downey Creek pluton, are aligned parallel to the syn-kinematic foliation on a regional scale. These dikes can be observed to contain a solid-state foliation parallel to the regional foliation. B) Closer inspection reveals the dikes crosscutting the regional foliation.

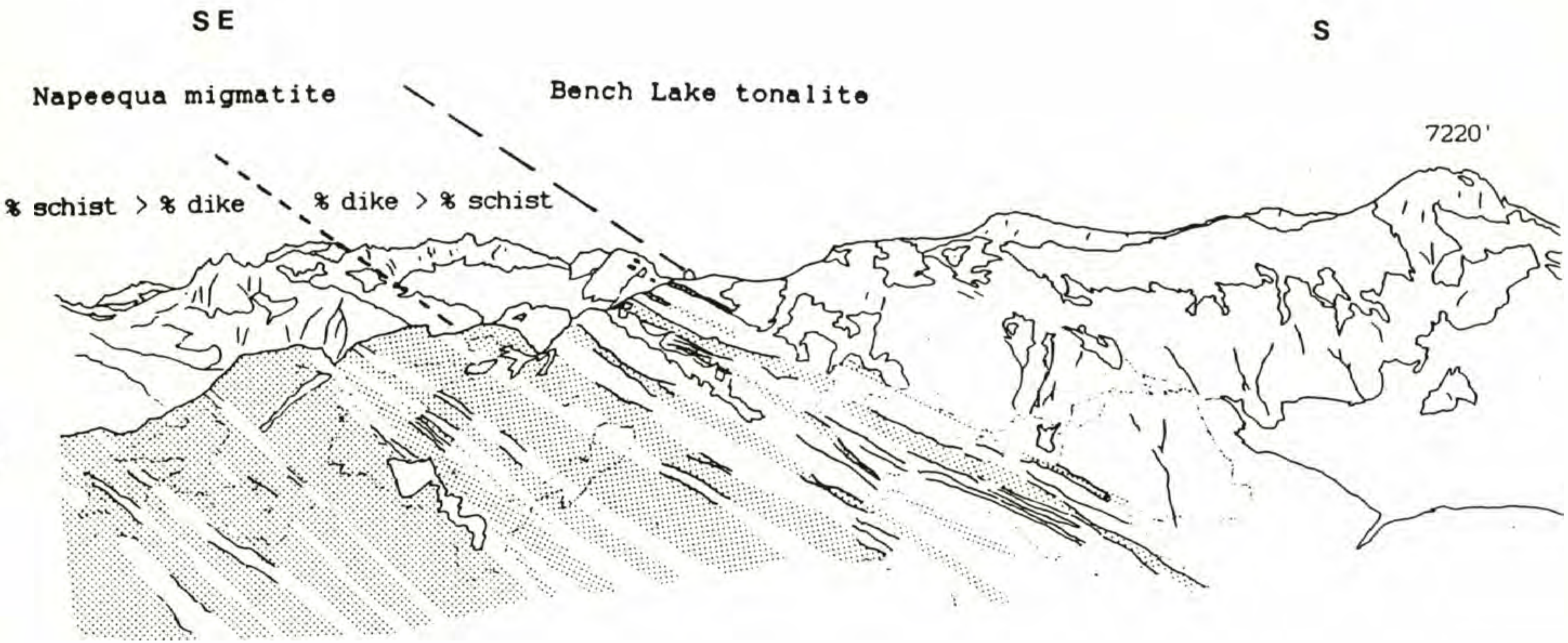


Figure 26. Sketch of southwest trending ridge leading to peak 7220' (Mt. Bruseth). Shows gradation of contact between the Napeequa migmatite and the Bench Lake tonalite. Schist of the migmatite is stippled. Approaching the pluton, dikes in the migmatite become larger and more abundant. The dikes appear to originate from the pluton and are thought to be related to the emplacement of the Bench Lake pluton.

plutonic rock contain magmatic epidote indicating that both were emplaced at pressures greater than 6 Kb (Hammarstrom and Zen, 1986). Several samples collected for petrographic and isotopic study by Ford et al. (1988) are mapped as belonging to the Bench Lake pluton (plot #'s 9, 12, 13, and 16, Ford et al., 1988). However, subsequent mapping revealed that these samples were taken from areas mapped well within the boundary of the Napeequa migmatite (plot #'s 12,16, Tabor et al., 1988; plot #'s 9,13, plate 1 of this study). Modal analyses of these samples are indistinguishable from samples of the main pluton body.

Whether these dikes actually originate from the pluton or are coalescing as feeders building up the pluton is uncertain. It is clear, however, that the migmatite is an injection zone associated with the emplacement of the Bench Lake pluton.

The dikes contain a solid-state deformational fabric that parallels the syn-kinematic regional foliation. Deformation occurring after the dike injection is evident from boudinage structures. The dikes also can be observed to crosscut the regional foliation in places (Fig 27).

Northern Plutons

Cyclone Lake granodiorite - The Cyclone Lake pluton displays a solid-state deformational fabric expressed as a weak to moderate foliation. The fabric generally strikes northwest throughout the pluton, concordant with the regional foliation. The nature of the contact with the country rock schist was not established. The

A

B

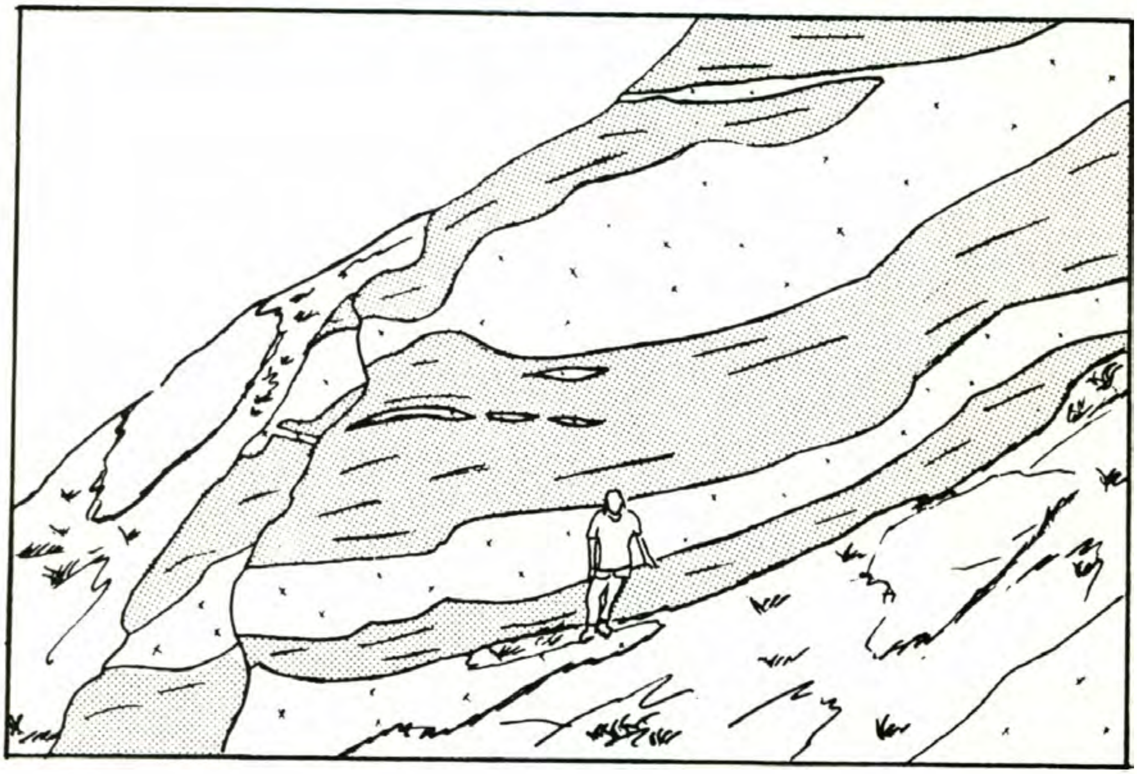


Figure 27. Dikes in the Napeequa migmatite, closely associated with the Bench Lake pluton, contain deformational features related to the syn-kinematic foliation. A. Dike parallel to regional foliation also contains a solid-state deformation concordant with the foliation. Closer inspection reveals that this dike also crosscuts the foliation. B. Dikes, generally parallel to regional foliation, display boudinage structures and crosscutting relationships.

relationship is unknown due to lack of exposure and the fact that the pluton is mostly in contact with the Jordan Lake and the Tertiary Buckindy plutons.

Thermobarometry performed on a screen within the Cyclone Lake pluton yielded high temperature but pressure lower than those obtained for the peak metamorphism of nearby country rock. The equilibrium assemblage in the screen rock could have been reset by the pluton and reflect conditions at the time of emplacement. However, there is no textural evidence of retrograde metamorphism. The depth of crystallization for the Cyclone Lake pluton is uncertain.

Jordan Lake tonalite - The Jordan Lake pluton is largely undeformed except for the outcrops on the ridge between Kindy and Found Creeks where the rock displays a strong foliation parallel to regional foliation. The contact with the Napeequa unit is exposed in several places and clearly shows the pluton crosscuts the country rock fabric. Hornblende barometry in the pluton suggests emplacement at depths less than those obtained for the country rock.

Discussion

Although no single criterion can be used to determine the relationship between plutonism and deformation, the relative timing can be established through a combination of structural and metamorphic observations. All foliations examined in the plutons and the dikes of the Napeequa migmatite, as described in the lithologies section, are attributed to solid-state deformation, following criteria of Paterson et al.

(1989). Evidence was sought for textures related to post-tectonic solid-state deformation associated with pluton emplacement, such as those found in a ballooning diapir (Bateman, 1985), but none were found. Therefore, solid-state deformation in these plutons can be attributed, with reasonable confidence, to either pre- or syn-tectonic emplacement.

A summary of structural and metamorphic observations for each pluton with interpretations of relative timing of emplacement is listed in table 3. Plutonism in the southern high grade portion of the study area appears to be coeval with peak metamorphism. The evidence suggests that the Downey Creek and Bench Lake plutons in the southern region of this study and the Sulphur Mt. pluton further south are syn-tectonic and were emplaced synchronously with metamorphism. A late syn-tectonic emplacement is inferred for the Cyclone Lake pluton. The Jordan Lake pluton is interpreted to be late syn- to post-tectonic. Also, the spatially related Chaval pluton is reported to have a magmatic foliation and a post-tectonic emplacement (Bittenbender, 1991).

Table 3. Summary of observations and interpretations of the relative timing for Cretaceous plutons.

Pluton	Age	Structures	Metamorphism	Interpretation
Sulphur Mt.	96†	not observed this study	barometry of pluton coincident with country rock	syn-tectonic
Downey Ck.	95*	ss deformation in pluton ss deformation in dikes dikes truncate regional foliation	no barometry of pluton	syn-tectonic
Bench Lk.	95*	ss deformation in pluton ss deformation in dikes dikes boudinaged dikes truncate regional foliation	barometry of pluton coincident with country rock	syn-tectonic
Cyclone Lk.		ss deformation in pluton	uncertain barometry of screen within pluton less than country rock	late syn-tectonic
Jordan Lk.	73†	mostly undeformed	barometry of pluton less than country rock	late syn- or post-tectonic

* Age inferred to be that of dikes in adjacent migmatite (Walker, pers. comm.).
† Walker and Brown, 1991. All ages in Ma.

Timing of Peak Metamorphism

The Sulphur Mt. and Bench Lake plutons were emplaced at depths equal to peak metamorphism of the country rock. Dike rock of the Napeequa migmatite, associated with the Downey Creek and Bench Lake plutons, display textures indicating injection was ongoing during metamorphism and deformation. Dougan (1992) collected samples of the dike rock for zircon U/Pb geochronology that yielded concordant ages of 95 Ma (Walker, pers. comm.). This age, combined with the age of the Sulphur Mt. pluton (96 Ma, Walker and Brown, 1991), indicates that peak metamorphism took place around 95-96 Ma in the southern, high grade region.

Bittenbender (1991) reported that the 92 Ma Chaval pluton is undeformed and displays a magmatic foliation. He also reported a 93 Ma non-foliated dike crosscuts metamorphic fabric of the Chiwaukum schist. Thus metamorphism is presumed to have occurred prior to 93 Ma in the vicinity of the Chaval pluton.

By 73 Ma, pressures in the northern region were below 2 Kb, bracketed by intrusion of the Jordan Lake pluton. Field relations at the contact show that the undeformed pluton clearly crosscuts the metamorphic fabric of the Napeequa unit. Emplacement is considered post-metamorphic indicating pressures in the northern region to be less than 2 Kb by 73 Ma.

STRUCTURE

Introduction

Fabric elements include a well-developed metamorphic foliation, mineral lineations, and folds. Regionally, these fabrics are overprinted by minor folding and static retrograde metamorphism. In the northern region, a localized mylonite with NNW left-lateral shear indicators overprints metamorphism.

Regional Fabric

Foliations

In the study area, foliations dominantly strike northwest to southeast and mostly dip moderately to steeply to the northeast or steeply to the southwest. All of the metamorphic rocks and Cretaceous plutons, with the possible exception of the Jordan Lake pluton, possess this penetrative fabric to some degree. Figure 28 shows the strike and dips of the metamorphic foliation in the study area. In the schists and phyllites of the Napeequa and Chiwaukum units, the foliation is usually defined by the alignment of recrystallized and elongate micas, amphibole, quartz, and feldspar along compositional layering. Plutonic rocks generally display foliation by the alignment of recrystallized quartz and feldspar parallel to micas and accessory minerals. Textures defining the foliation in metamorphic and plutonic rocks are further described in the lithologies section.

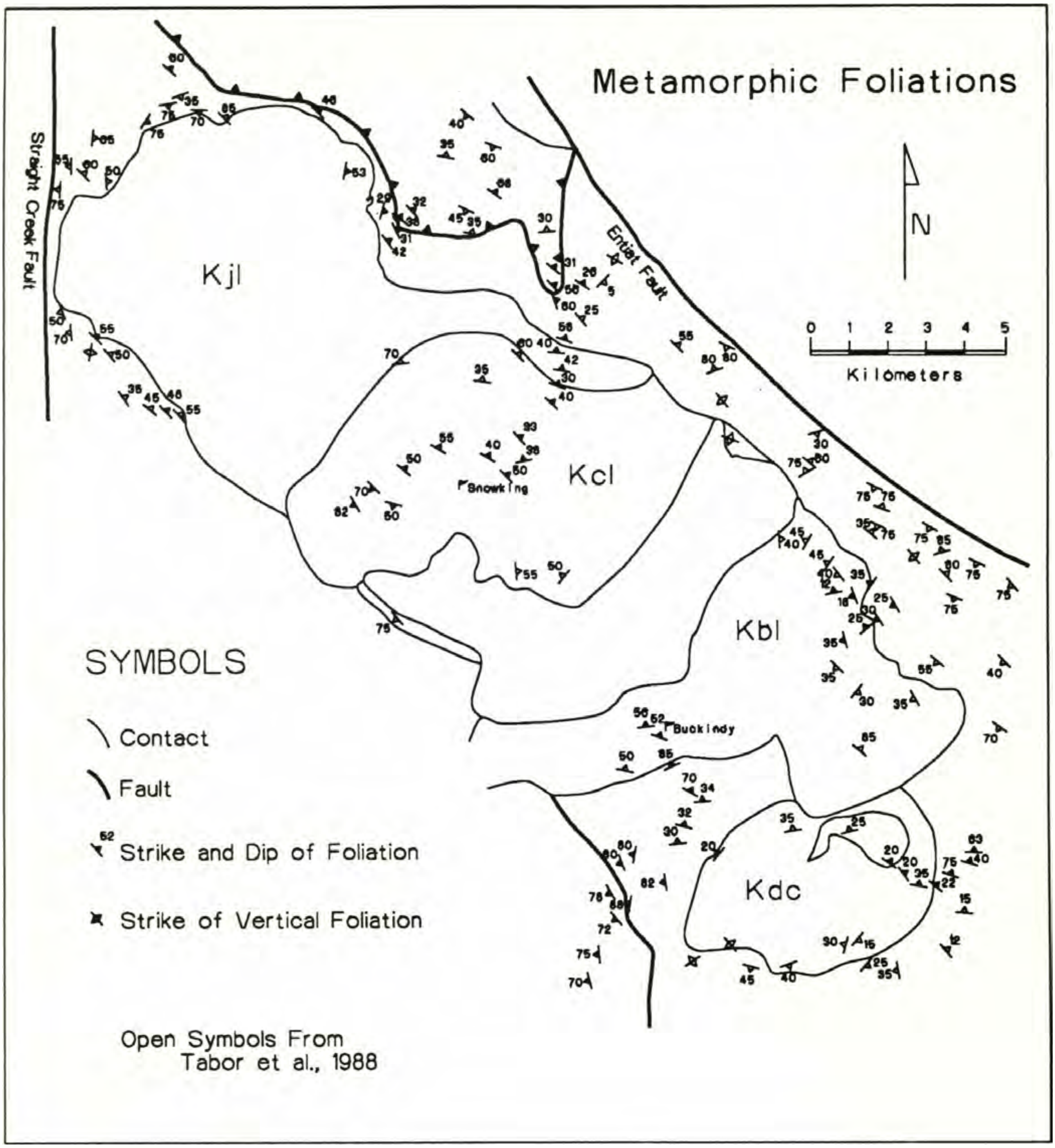


Figure 28. Map of study area showing strike and dip of metamorphic foliations. Geologic units same as figure 5.

Lineations

Most mineral lineations are defined by the alignment of biotite or amphibole minerals within the foliation plane of schistose rocks. The lineations generally trend southeast or northwest with a shallow to moderate plunge (Fig 29). Although kinematic indicators are generally absent in the amphibolite grade rocks of the Napeequa and Chiwaukum units, some micro-structures do exist that indicate non-coaxial deformation was ongoing during metamorphism. One specimen in this study area displays convincing syn-metamorphic kinematic indicators. A garnet-staurolite schist of the Chiwaukum unit contains idioblastic garnets with graphite inclusion spirals indicating a dextral shear sense (Powell and Vernon, 1979)(Fig 30). A dextral sense of shear has been determined for kinematic indicators in rocks of adjacent areas (Longtine, 1991; Bittenbender, 1991). Dextral shearing during orogenesis has been documented throughout the crystalline core (Brown and Talbot, 1989; Miller et al., 1989; Dragovich, 1989; Cary, 1990; and McShane, 1992). The paucity of kinematic indicators for this region of the CC can be attributed to recrystallization accompanying high grade metamorphism (Simpson, 1985; Mawer, 1987).

Deformation

The main phase of deformation occurred at the time of peak metamorphism. A flattening fabric, defined by the metamorphic foliation, formed during this time. The flattening is accompanied by isoclinal folding that is recognized by small-scale

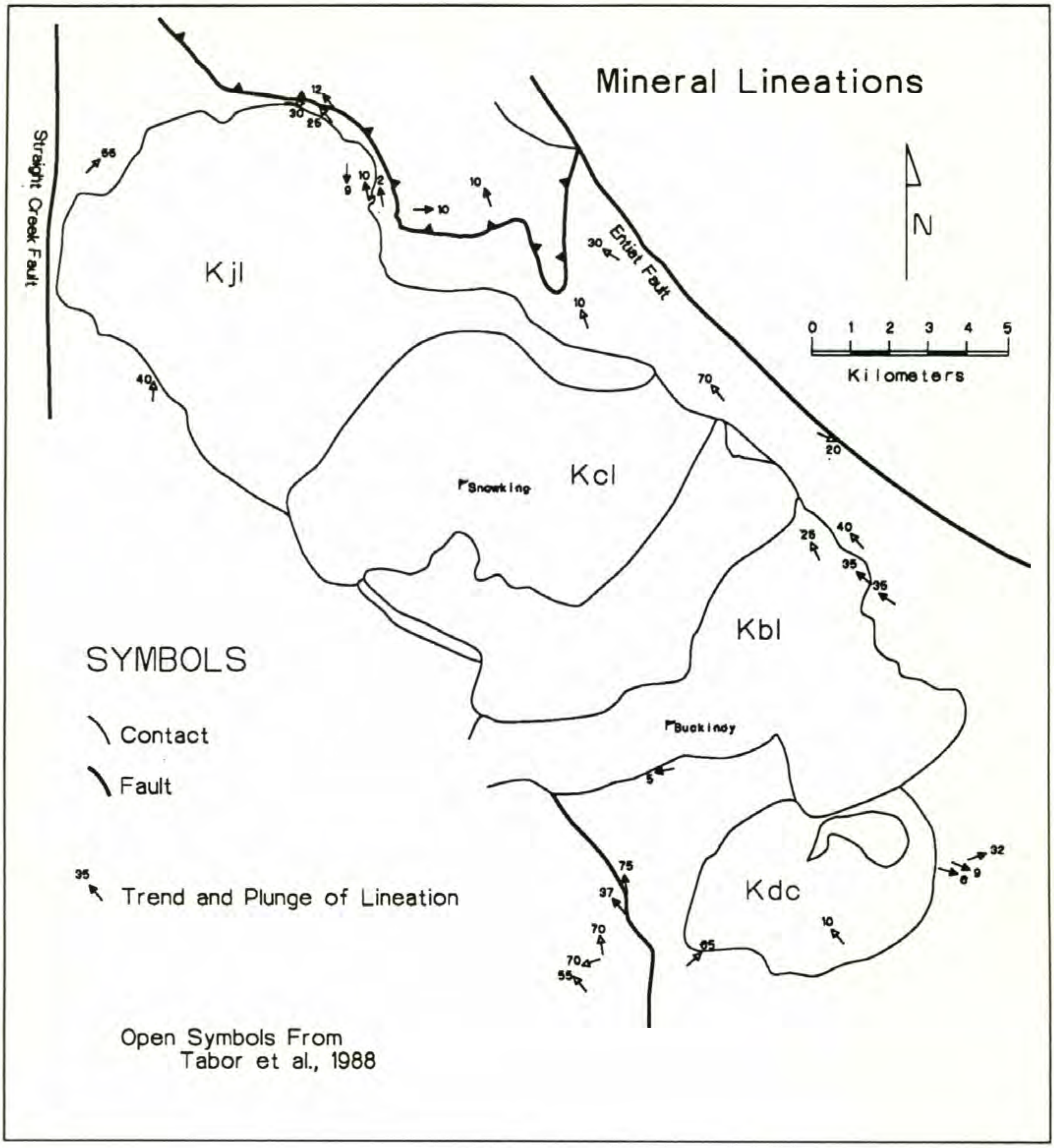


Figure 29. Map of study area showing trend and plunge of mineral lineations. Geologic units same as figure 5.

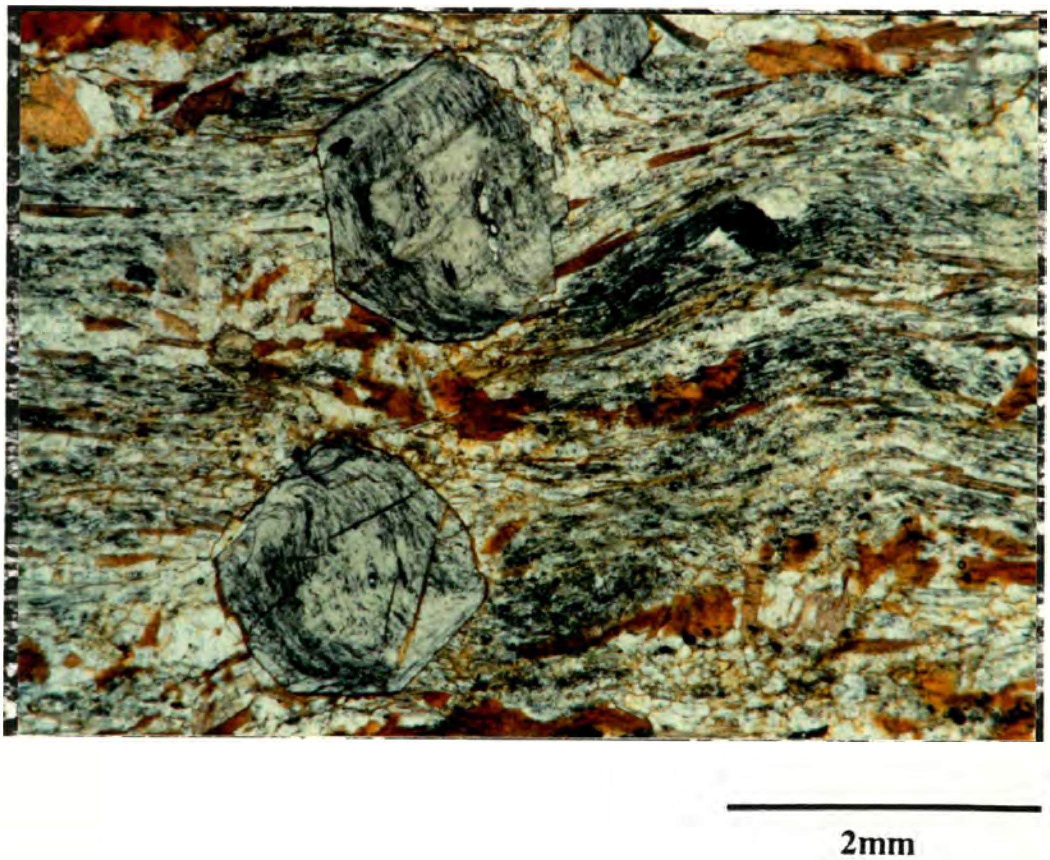


Figure 30. Dextral shear sense is evident from graphitic inclusions incorporated during garnet growth (specimen 174-45b). Photomicrograph is taken in plane polarized light from a graphitic staurolite-garnet schist of the Chiwaukum unit found near the Napeequa-Chiwaukum contact.

isoclinal folds in outcrops. The axial plane of the folding is parallel to the foliations at outcrop scale.

The deformation that occurred during metamorphism is generally folded by open folds and by a pervasive crenulation cleavage found on the S-surfaces.

Discussion of the Nature of the Marblemount-Napeequa Contact

The increase in strain intensity along the southern and southwestern margin of Mmqd, and the juxtaposition of the ocean floor rocks of the Napeequa unit with the oceanic arc plutonic rocks of the Marblemount unit, have led to an interpretation that the contact between the Marblemount and Napeequa units is a thrust (Tabor et al., 1988). Strain intensity is manifest by two different fabrics: 1) a gneissic fabric that appears to have formed during metamorphism, and 2) a mylonitic fabric that appears to have formed after metamorphism. The mylonite crops out along the southwestern margin of MMQD, whereas the southern margin is gneissic. However, not all of the margin was examined for this study, and further work is necessary to establish the extent of the two fabrics.

Metamorphic studies reveal that in the southern portion of MMQD, metamorphic index minerals partially define the gneissic fabric found along the pluton margin. Furthermore, isograds in the region appear to crosscut the Marblemount-Napeequa contact. These features indicate that MMQD was in place before or during the metamorphic event.

The gneissic fabric could be related to the regional foliation. A regional foliation need not penetrate a pre-tectonic pluton (Paterson et al., 1989). The increase in fabric intensity around the margin of the pluton could be due to contrasting rheology between the country rock and the pluton. Alternatively, the gneissic fabric could be related to a thrust contact. An intrusive pre-tectonic contact cannot be discounted. Clearly, more work is needed to resolve the nature of the Marblemount-Napeequa contact. The thrust interpretation is open to question.

Sinistral Shearing in the Northern Area

A complicated sinistral shear deformation is recorded in rocks in the northern part of the study area. Good exposure northeast of Granite Lakes, between peaks 6559' and 6110' (Razorback Mt.), allows for a careful examination of fabrics formed along the southwest margin of the Marblemount meta-quartz diorite, the Napeequa unit, and locally within the Jordan Lake granodiorite. A geologic map of the region is shown in figure 31.

Marblemount mylonite and Napeequa contact

Outcrop along the southwest margin of the Marblemount varies from coarse to fine grained green mylonite, with the fine grained mylonite being most abundant. Coarse grained mylonites contain a nearly horizontal mineral lineation generally trending north by northwest on the foliation surface. Parallel to the lineation and

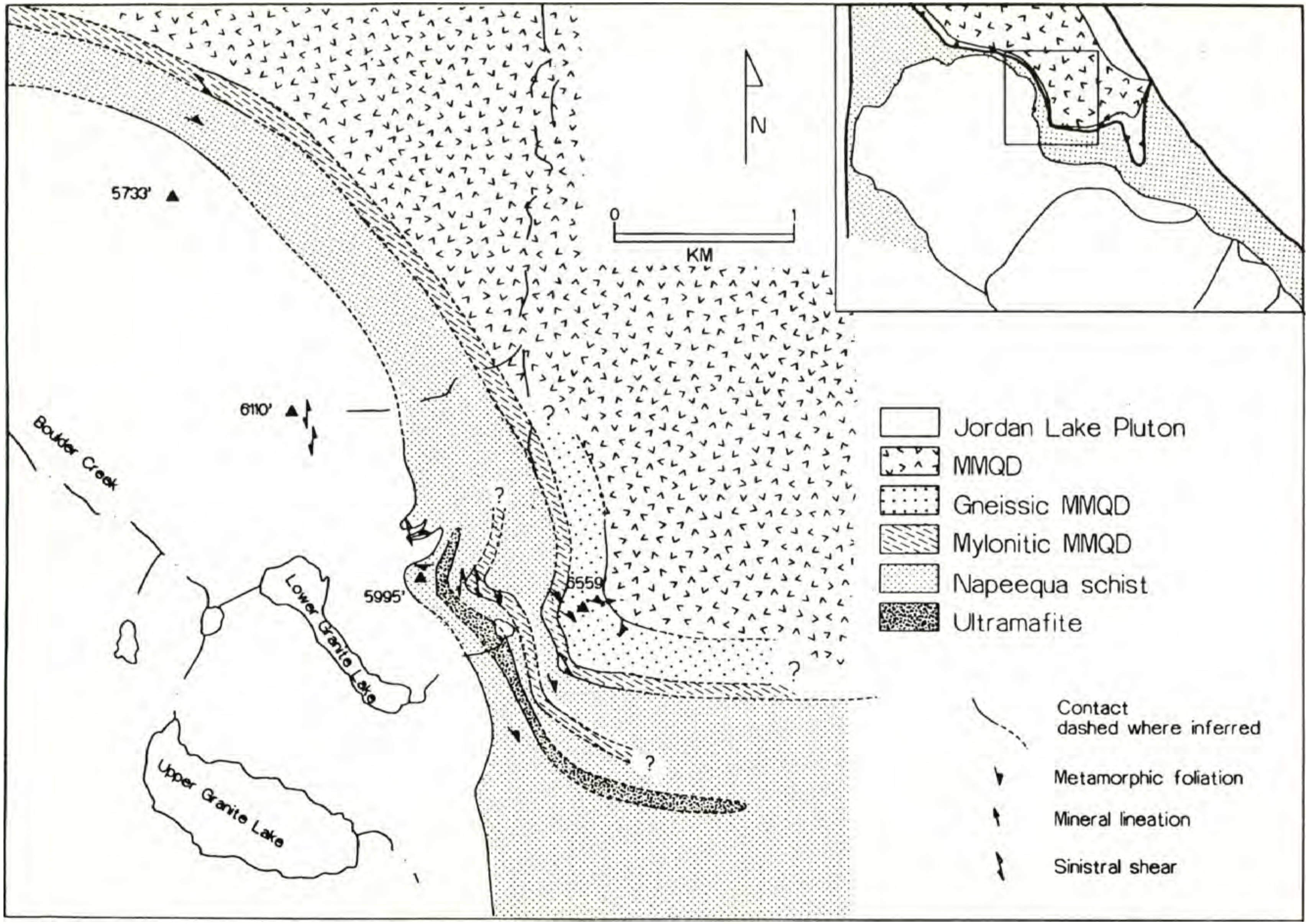


Figure 31. Geologic map of the northern study area in the vicinity of Granite Lakes. Sinistral shear is recorded in mylonitic rocks along the margin of Marblemount-meta quartz diorite, in the Napeequa schist near the Marblemount-Napeequa contact, and locally within the Jordan Lake pluton.

perpendicular to foliation, meso- and micro-structures show two foliation planes. S-planes (schistosity) make up the foliation surface and are defined by the alignment of feldspar porphyroclasts and aggregates, quartz ribbons, and epidote aggregates. C-planes are defined by recrystallized feldspar and epidote and reoriented quartz ribbons. The two planes intersect at angles up to 35 degrees and indicate a sinistral shear deformation (Berthe et al., 1979)(Figs 10A, 32).

Fine grained mylonites make up the bulk of the mylonitic rock. These rocks can be described as ultramylonites that probably formed by progressive deformation of the coarser grained mylonite. The ultramylonites are composed dominantly of recrystallized aggregates of feldspar, epidote, quartz, and chlorite. Only one foliation surface is present. Presumably, the S- and C-surfaces coincide due to high strain (Berthe et al., 1979). Kinematic indicators are less abundant. However, a sense of shear is recognized in samples with sparse coarse grains. Sinistral shearing is indicated by broken plagioclase grains and asymmetrical augen (Simpson and Schmid, 1983)(Fig 33).

The foliation of the mylonite zone is continuous across the contact from the MMQD into the Napeequa unit. Kinematic indicators found in the mylonite are generally absent in the Napeequa biotite schist possibly due to a difference in competency in the schist or the annealing of microstructures. One specimen does contain asymmetric growth of quartz grains in pressure shadows of garnets that indicates sinistral shearing (Fig 34).

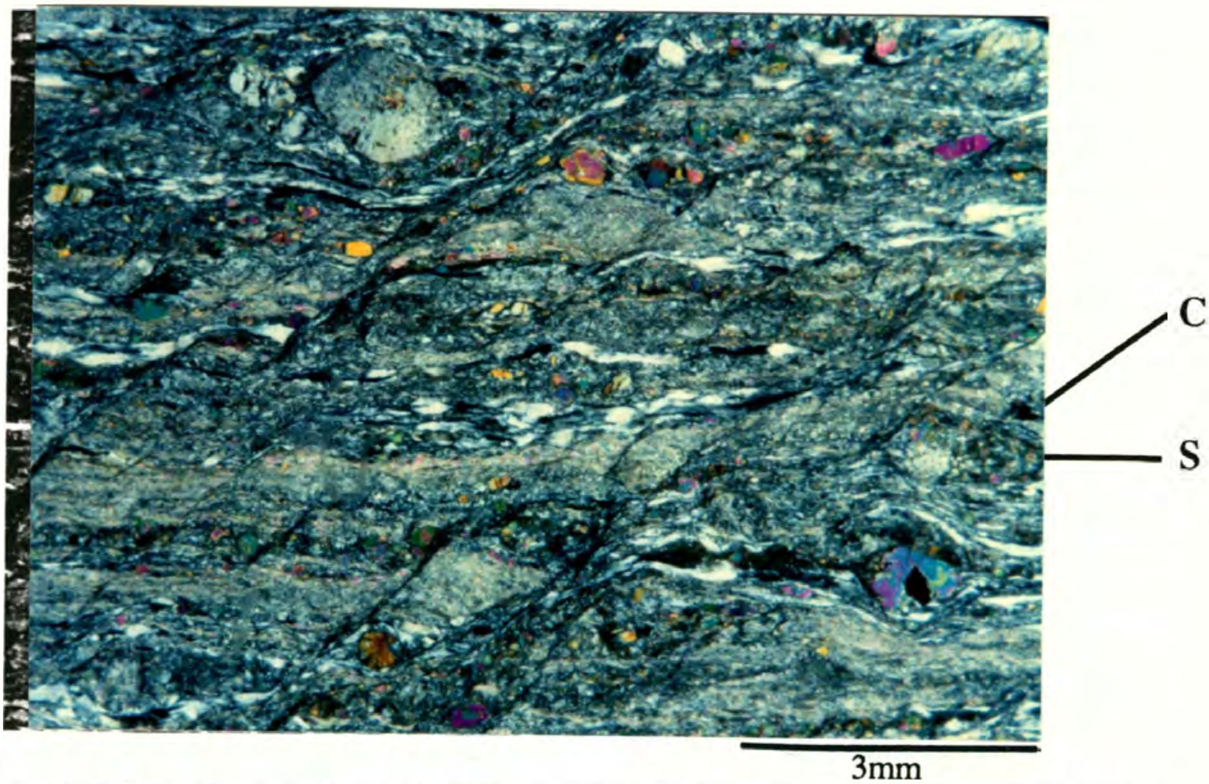


Figure 32. Photomicrograph of S-C fabric in coarse grained mylonite found along the SW margin of the Marblemount pluton (specimen 174-128b). S and C planes, defined by quartz ribbons and recrystallized epidote and plagioclase, formed after metamorphism and during sinistral deformation. Thin section is cut from bottom of specimen, parallel to mineral lineations, and normal to foliation. Plane polarized light.

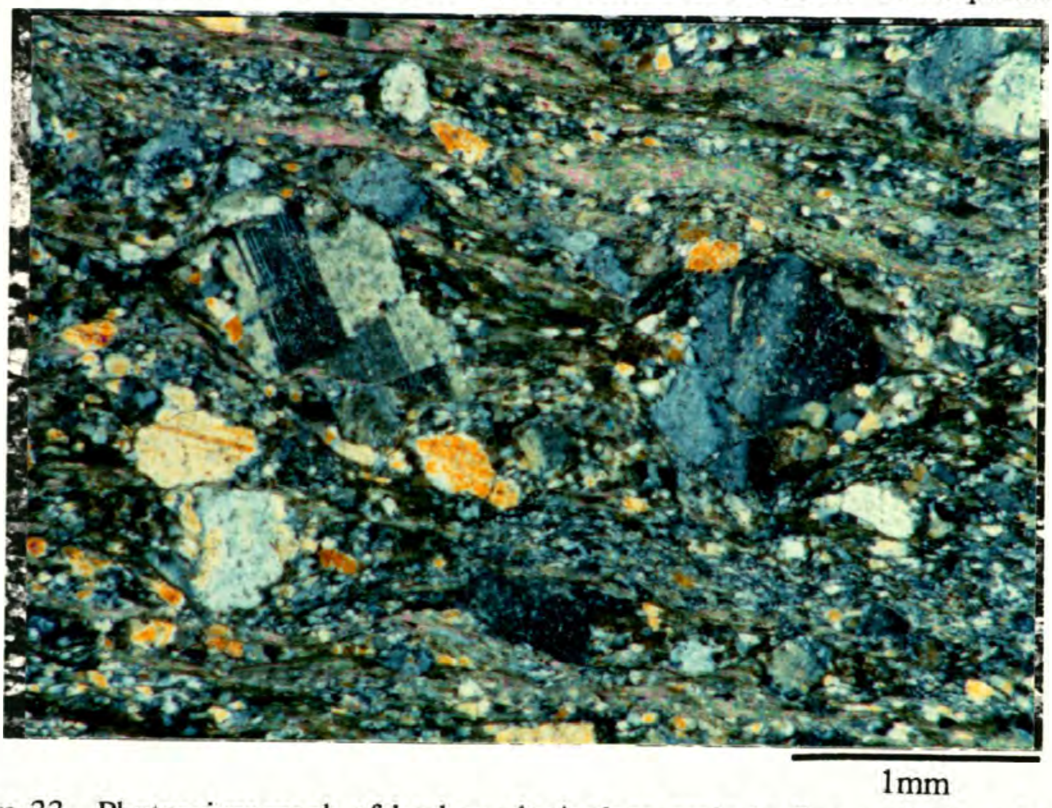


Figure 33. Photomicrograph of broken plagioclase grain in fine grained mylonite of the Marblemount unit showing sinistral shear. Thin section is cut parallel to mineral lineation and normal to foliation (specimen 164-267). Crossed nichols.

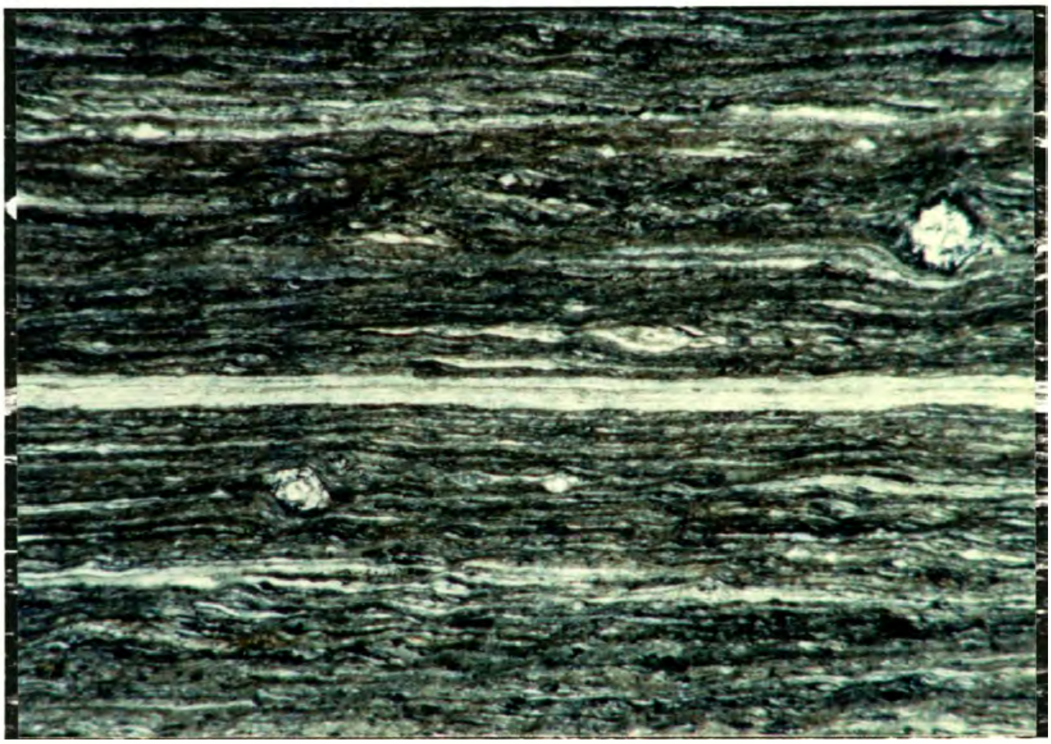


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Figure 34. Asymmetric quartz growth in pressure shadows of garnet indicate sinistral shear in the Napeequa unit. Thin section is cut parallel to mineral lineation and normal to foliation (specimen 174-120a). This quartz-biotite schist of the Napeequa unit is from near the contact with mylonitic MMQD. Plane polarized light.

Evidence for sinistral deformation in the Napeequa schist near the Marblemount mylonite is sparse. Foliation and rare mineral lineations in the schist are consistent with the mylonite fabric indicating that fabrics in both units developed during the same deformation.

Jordan Lake granodiorite

The Jordan Lake pluton crosscuts the fabric developed during sinistral shearing recorded in the Marblemount and Napeequa units. However, the Jordan Lake pluton also contains a left-lateral shear zone with the same general orientation. On peak 6110' (Razorback Mt.) an extensive shear zone greater than 200 m long and approximately 3 meters wide is found (Fig 35). Sinistral shearing within this zone is evident from broken plagioclase grains, asymmetrical plagioclase augen, and biotite fish (Simpson and Schmid, 1983)(Fig 36A).

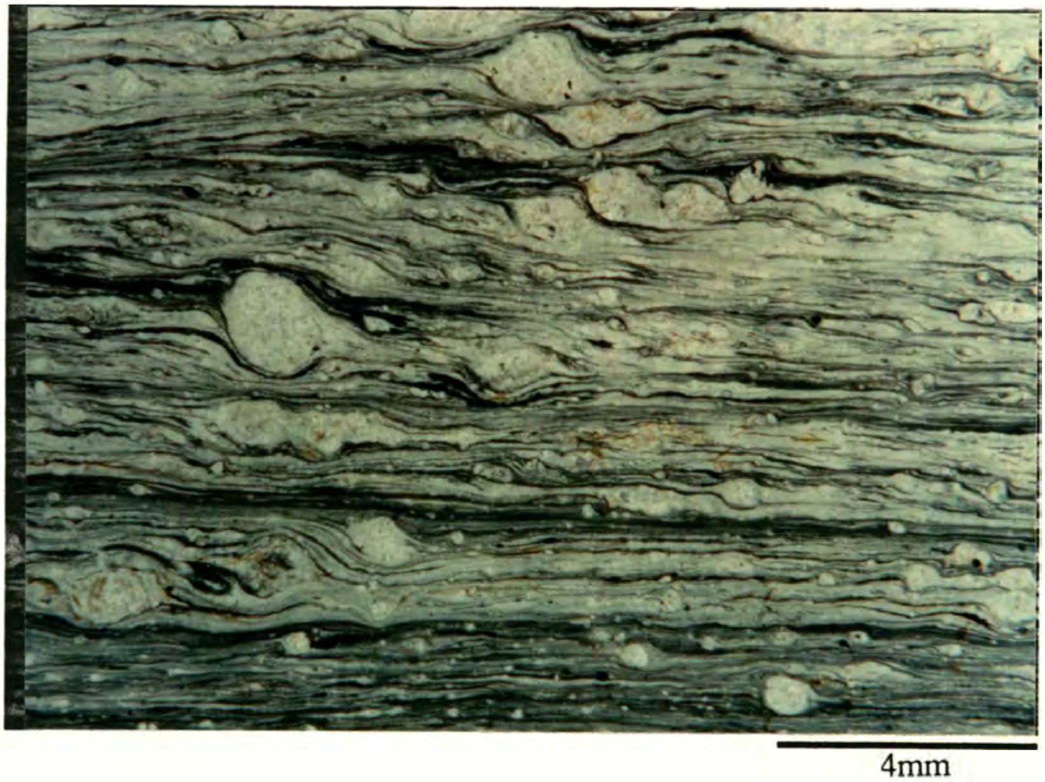
Farther south, near peak 5955', sinistral deformation is evident in mylonitic Jordan Lake granodiorite (Fig 36B). Locally, the mylonite is folded by a large open fold with an east trending fold axis.

Discussion

The mylonite unit of MMQD overprints metamorphic minerals and thus is interpreted to have occurred after metamorphism and the formation of the gneissic fabric. The Jordan Lake pluton crosscuts the fabric of the Napeequa unit, a fabric that appears to have formed with the mylonite unit of MMQD, indicating that the deformation in this region formed before 73 Ma. A sinistral deformation fabric is also recorded locally in the Jordan Lake pluton. Left-lateral non-coaxial deformation was ongoing after peak metamorphism in this region.

Figure 35. Photograph looking northwest of shear zone found in the Jordan Lake pluton on Razorback Mt. (peak 6110'). The shear zone can be seen in the notch between the two non-vegetated peaks. It is approximately 3 meters wide and displays meso- and micro-textures indicating sinistral deformation. The blank face on the left is the approximate orientation of the S-surface. Orientation of the shear zone and mineral lineations within are consistent with the trend of fabrics found in the Marblemount mylonite and Napeequa schist nearby. However, the pluton crosscuts the latter fabric and is mostly undeformed.

A



B

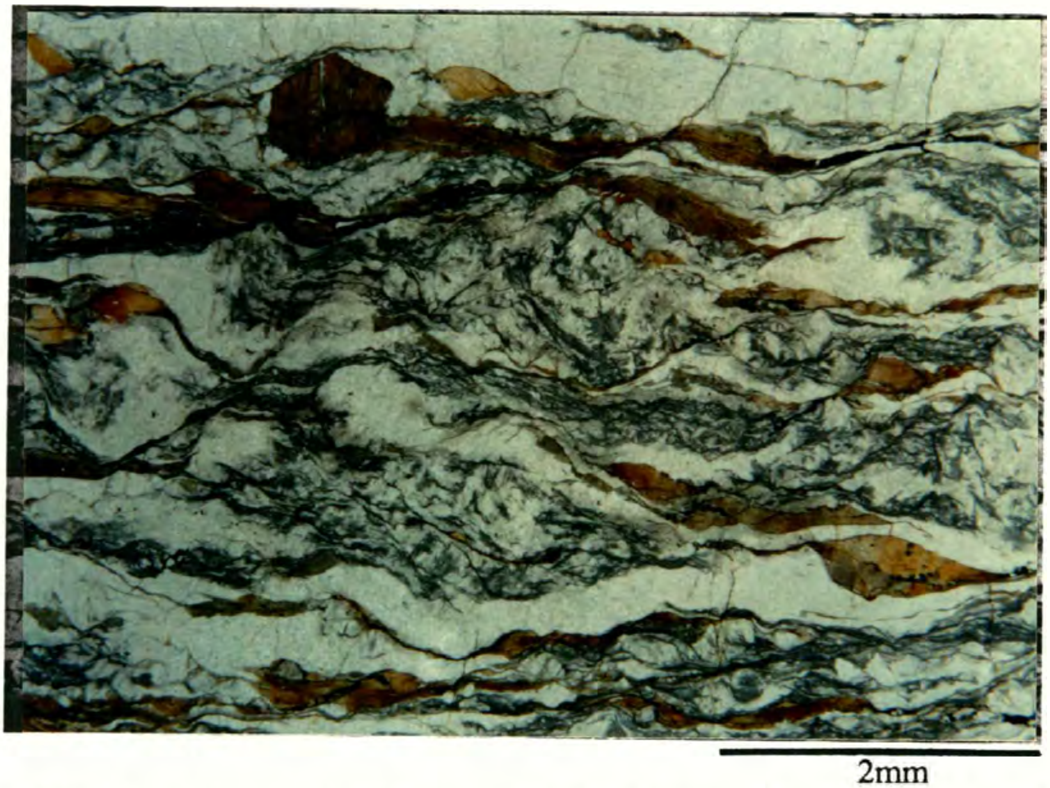


Figure 36. Photomicrograph of sinistral shear-indicators of mylonitic Jordan Lake tonalite. A) Asymmetric plagioclase augen and biotite fish in a coarse grained mylonite (specimen 174-129). B) Asymmetric plagioclase augen in a fine grained matrix taken from the bottom of the specimen (specimen 174-109). Both sections were cut parallel to mineral lineations and normal to foliation. Plane polarized light.

The significance and cause of post-metamorphic sinistral deformation is not fully understood. Possibly, motion along the shear zone can be attributed to block rotation driven by the dominantly dextral motion on the Tertiary Straight Creek and the Entiat faults.

SUMMARY OF FINDINGS

In the Mt. Buckindy/Snowking region of the North Cascades crystalline core, mid-Cretaceous metamorphism was accompanied by plutonism. Metamorphism in the area varies from lower greenschist facies in the northwest to upper amphibolite facies in the south. Isograds delineating metamorphic zones crosscut the Marblemount/Napeequa contact indicating that the Marblemount unit was thrust into place or at least in contact with the Napeequa unit before peak metamorphism. Thermobarometry of country rock has delineated isobars that are normal to the regional penetrative metamorphic fabric and the orogen. Pressures range from less than 4 Kb in the northwest to over 9 Kb in the southeast.

Cretaceous plutons in the area are dominantly granodioritic to tonalitic. In the southern, high-grade portion of the study area, the Sulphur Mt., Downey Creek, and Bench Lake plutons were emplaced at deep levels in the crust during the peak metamorphic event, approximately 95 to 96 Ma. The Cyclone Lake and Jordan Lake plutons in the northern portion of the study area appear to have been emplaced at shallower levels in the crust. By 73 Ma metamorphism ceased as recognized by the intrusion of the generally undeformed Jordan Lake pluton.

A penetrative metamorphic foliation in the area dominantly strikes northwest and dips steeply to the southwest or northeast or moderately to the northeast. Mineral lineations found within this foliation display various orientations, but shallow to moderately plunging orogen-parallel lineations dominate. Evidence for northwest oriented non-coaxial, dextral shear strain is found, but is sparse in this area. Workers in adjacent areas to the north and southeast of this study have found more abundant evidence of this type of strain.

North to northwest directed non-coaxial, sinistral shear strain is recorded in rocks in the northern area. This deformation is post-metamorphic and appears to have occurred before and after the emplacement of the 73 Ma Jordan Lake pluton. A possible cause of the shear is block rotation as a result of dextral motion along the Straight Creek and Entiat faults.

DISCUSSION

Regional Implications

Barrovian style metamorphism has long been recognized in the crystalline core (Misch, 1966). A metamorphic gradation of lower greenschist and upper amphibolite facies has previously been mapped. Recently, thermobarometry has been applied to quantitatively determine pressures and temperatures reached during peak metamorphism. Pressures as great as 9 Kb have been obtained in the Skagit complex (Whitney and McGroder, 1989). In order to understand the metamorphic history of the crystalline core (CC) the relative timing of regional metamorphism and plutonism must be established.

This study has determined that peak metamorphism in the vicinity of Mt. Buckindy and Snowking Mt. occurred around 95-96 Ma, the ages of syn-tectonic plutons and dikes. Work in other parts of the CC has demonstrated that regional metamorphism is diachronous. To the east and northeast of this study area, across the Entiat fault, metamorphism was ongoing from late-Cretaceous to mid-Eocene time. Rocks in the Skagit complex, juxtaposed to the northeast of this study area by the Entiat fault, record upper amphibolite facies metamorphism. McShane (1992) has delineated orogen parallel isobars increasing to the northeast from 6 to 9 Kb. The timing of burial and subsequent metamorphism in this area is restricted to a period between 88 and 75 Ma. In the northeastern CC, Miller et al. (1989) have documented amphibolite facies assemblages and solid-state foliations in a belt of 68 to 59 Ma plutons. In addition, to the south of this study in the vicinity of Sloan Peak, amphibolite facies metamorphism commenced prior to 90 Ma and ceased by 75 Ma (Longtine, 1991). These investigations show that localized pulses of plutonism and metamorphism are distributed throughout the CC.

Relation to Orogenic Models

Recent orogenic models for the CC are summarized in the introduction to this report. The models invoke fundamentally different mechanisms for the cause of metamorphism. One model is based on regional contraction by way of a regional southwest directed thrusting event. Another model cites plutonism as the cause of high grade metamorphism. The models predict disparate effects related to the plutonism and metamorphic history of the CC. Findings for all parts of the CC must fit these models.

Evidence from this study does not support a hypothesis that peak metamorphism was caused by regional, southwest directed thrusting. Instead, metamorphism in this region can be attributed to a localized, orogen-parallel load rooted in the southeast, and emplaced toward the northwest. A magmatic loading model is supported here. The conclusions of this study with particular significance relating to the models are as follows.

1) Orogen-normal isobars increase from less than 4 Kb in the northwest to over 9 Kb in the southeast. Southwest directed thrusting would create orogen-parallel isobars increasing to the northwest. A magmatic loading model can accommodate localized high pressure loading. Baric gradients, controlled by magmatic emplacement, could be oriented with highest pressures towards the source of loading. Orogen-normal isobars observed in this study would suggest loading originated from the southeast.

2) Peak metamorphism is dated by relation of minerals and fabric to be coeval with 95 to 96 Ma plutonism. In the North Cascades thrusting model, thrusting is suggested to have taken place 100 - 84 Ma (Brandon et al., 1988; McGroder, 1991). Based on the assumption that anatectic melt from a depressed crust would be expected to lag thrusting by approximately 20 My (Zen, 1988), the earliest thrust-related plutonism would occur around 80 Ma.

3) Peak metamorphism occurred 95 to 96 Ma, which is older than that found in other parts of the CC. A mid-Cretaceous thrusting event ending by late-Cretaceous time does not adequately explain the observed diachronous metamorphism. Ongoing

magmatic pulses accompanied by metamorphism would be reasonably expected in a magmatic arc. Diachronous metamorphism is consistent with magma loading.

Although a magma loading model is favored here over the thrust model for the crystalline core, several less-likely possibilities exist for the metamorphic and plutonic history of the CC. For example, apparent diachronous metamorphism could be the result of metamorphic reactions being activated by the infiltration of fluids associated with localized plutonic events. Baric gradients could reflect mineral metastability. Furthermore, pressure gradients could be affected by faulting or folding of previously metamorphosed rocks. This study did not reveal evidence supporting these processes.

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APPENDIX 1
MINERAL ASSEMBLAGES

Mineral abundance:
O > 20%, 20% > X > 5%, 5% > x > 1%, tr < 1%
Abbreviations:
Qtz=quartz, Pla=plagioclase, Ksp=K-feldspar, Bio=biotite, Mus=muscovite, Hbl=hornblende, Chl=chlorite, Ep=epidote, Sph=sphene, Rut=rutile, Ap=apatite, Zir=zircon, Gar=garnet, Op=opaques (o=oxides), Cc=calcite, Gra=graphite, St=staurolite, Ant=antigorite, Tlc=talc, For=forsterite, Trm=tremolite, Amp=amphibole, magma Ep=magmatic epidote, barom=sample used for microprobe analysis and thermobarometry, sin=sinistral shear, dex=dextral shear.

Mule Lake Area

Specimen	Qtz	Pla	Ksp	Bio	Mu	Hbl	Chl	Ep	Sph	Rut	Ap	Zir	Op	Other	Comments
Downey Ck. granodiorite															
174-2a	O	O	X	x	x		x	x			tr	tr	o		
174-10	O	O	X	x	x		x	x		tr		tr		Gar	
174-12b	O	O	X	x	x			x	tr	tr	tr			Gar	
174-12c	O	O	X	x	x		x	x		tr	tr				
Napeequa migmatite - dikes															
174-1	O	O	X	x	X		x								
174-3c	O	O	X	x			x	tr			tr				
174-3d	O	O	X	x	x			tr							
174-4	O	O	X	x	x		X	tr	tr		tr				
174-9b	O	O	X	x	x			tr						Gar	

Specimen	Qtz	Pla	Bio	Mu	Hbl	Gar	Chl	Ep	Sph	Gra	Zir	Rut	Op	Other	Comments
Napeequa migmatite-schist															
174-3a	O	X	O				x	tr	x			tr			
174-3b	X	X	O				x		X			x			
174-3c	X	O	O			x	tr	x	X			x			
174-5a	O	O	O			X				x		tr			
174-6b	X	O			O			x				x			
174-7a	X	X			O			O				x			
174-8a															barom

Specimen	Ant	Tlc	For	Op	Ca	Qtz	Tr	Sph	Bio	Ep	Other	Comments
ultramafic												
174-6a	O	X		x								
marble												
174-6c					O	O	X	tr	tr	x		

Green Mt. to Mt. Buckindy

Specimen	Qtz	Pla	Bio	Mu	Hbl	Gar	Chl	Ep	Sph	Gra	Zir	Rut	Op	Other	Comments
Chiwaukum schist															
174-13a	X	X	X		X	x	x	x		x			o		
174-13b	X	x	X	x	x	x	x	x	x	x			o		
174-14	X	x	X			x	x			x		x	o		
174-15b	X	x	X		x	X	x	x					o		
174-15c	X	x	X		x	x	x	x		x	x	x	o		
174-45b	X	x	X	x		x	x			x			o	St	barom, dex
174-50	X	x	X		X	x	x					x	o		
Napeequa schist															
174-15a	X	x	X		X		x		x	x					
174-16a	X	x	x		X			x							
174-16b	X	x	X	x	X	x	x	x		x			o		
174-45a	X	x			X				x			x	o		
Napeequa migmatite-schist															
174-24	X	x	X		X	x		tr	tr				o		barom
174-46a	X	X	X				x	x				x	o		

Specimen	Ant	Tlc	For	Op	Others	Comments
ultramafic						
174-20	O	x	x	x		

Specimen	Qtz	Pla	Ksp	Bio	Mu	Hbl	Chl	Ep	Sph	Rut	Ap	Zir	Op	Other	Comments
Bench Lake tonalite															
174-26b	X	X	x	X	x		x		x			x	o		
174-27	X	X	x	X	x		x				x	x	o		geochron
174-28	X	X	x	X			x				x	x	o		
174-46b	X	X	x	x	x		x	x	x		x	x	o		
174-49	X	X	x	X	x	x	x	x	x		x	x	o		barom

Long Gone Lake Area

Specimen	Qtz	Pla	Ksp	Bio	Mu	Hbl	Chl	Ep	Sph	Rut	Ap	Zir	Op	Other	Comments
Bench Lake tonalite															
174-37a	X	X	x	X	x			x	x			x			magma ep
174-37b	X	X	x	X	x		x	x				x	o		magma ep?
174-38a	X	X	x	X	x		x	x	x		x	x			magma ep?
174-38c	X	X	x	x	x		x	x	x		x	x			magma ep?
174-39a	X	X	x	X	x		x	x	x			x			magma ep
174-39b	X	X	x	X	x		x	x	x		x	x			
174-40a	X	X	x	X	x		x	x			x	x			
174-41	X	X	x	X	x		x	x	x		x	x	o		magma ep
Napeequa migmatite-dikes															
174-36b	X	X	x	X	x		x	x				x	o		
174-44a	X	X	x	X			x	x			x			Gar	magma ep

Long Gone Lake Area Cont'd

Specimen	Qtz	Pla	Bio	Mu	Hbl	Gar	Chl	Ep	Sph	Gra	Zir	Rut	Op	Other	Comments
Napeequa migmatite-schist															
174-36a	X	X			O	x		X	x			tr			
174-36c	O	X	X		O	x		tr				tr			barom
174-43	X	X			O	x		X	x				o		
174-44b	X	O	x		O			x	x			x	o		

Snowking Mt. Area

Specimen	Qtz	Pla	Ksp	Bio	Mu	Hbl	Chl	Ep	Sph	Rut	Ap	Zir	Op	Other	Comments
Cyclone Lake granodiorite															
174-29a	O	O	X	X	x			x				tr	o		
174-29b	O	O	X	X	X		x	tr					o		
174-32	O	O	X	X	x		x					tr			
174-105	O	O	X	X	X		x	tr	tr	tr					
174-106	O	O	X	x	X		x	x				tr	o		
174-107	O	O	X	X	X		x	x							

Specimen	Qtz	Pla	Bio	Mu	Hbl	Gar	Chl	Ep	Sph	Gra	Zir	Rut	Op	Other	Comments
screen-schist															
174-33a	O	O	O	X		X		tr		X			o		barom

Granite Lakes Area

Specimen	Qtz	Pla	Ksp	Bio	Mu	Hbl	Chl	Ep	Sph	Rut	Ap	Zir	Op	Other	Comments
Jordan Lake granodiorite															
174-109	O	O			tr			x						cc	sin
174-110b	O	O	x	X	x	X		x	tr						
174-110c	O	O	x	X	x	x		x	x					cc	sin
174-122b	O	O	x	X	x	X		x	tr	tr	tr	tr			barom
174-125	O	O	x	X	x	X		x	tr						
174-129	O	O	x	X	x	x		x	tr					cc	sin
174-130															barom
Marblemount meta-quartz diorite															
174-114b	O	O		X	x	X	X	X	tr	tr					
174-114c	O	x			X		tr	x							
164-315a	O	O		X	x	X	x	X	tr	tr					
164-315b	O	O		X	x	X		X	x	tr					
164-315c	O	O			x	x	X	X		tr					
164-315d	O	O			x		x	X							

Granite Lakes Area Cont'd

Specimen	Qtz	Pla	Bio	Mu	Hbl	Gar	Chl	Ep	Sph	Gra	Ca	Rut	Op	Other	Comments
Mylonitic meta-quartz diorite															
164-180	O	O		x			X	O							sin
174-116a	O	O		X			x	X			x				
174-117b	O	O	x				x	X	tr		x	tr			
174-117c	O	O	x				x	X	tr			tr			
174-128b	O	O		x			x	X							sin
164-267	O	O		x			x	X							sin
164-314	O	O		x			x	O			x		o		sin
Napeequa schist															
164-181	O	O	x	x				x		x					
174-113	O	X	X	x			X			X		tr			sin
174-117a	O	O	X	x			X	x			x	tr			
174-118a	O	O	O		O	x				x		tr			barom
174-120a	O	X	X	x		x				O					sin
174-120b	O	x		X			X				x	tr	s		
174-120c	O	O		x						X				cc	
174-121	O	X	X					x	tr						
174-126	O	x	X				x	tr		x		tr			
164-265	O	x	X		x	X	X			x					

Kindy Ridge

Specimen	Qtz	Pla	Ksp	Bio	Mu	Hbl	Chl	Ep	Sph	Rut	Ap	Zir	Op	Other	Comments
Jordan Lake granodiorite															
174-108b	O	X	x	O	x	x	tr	x	tr		tr	tr			
164-408a	O	X	x	X	x	x	x	x	x		tr	tr			
164-408b	O	X	x	X	X	x	tr	x	x		tr	tr			
Gneissic meta-quartz diorite															
164-409	O	X		X	X			X	x	tr					
164-410a	O	X		X	x	X	X	O	tr						
164-410b	O	X		X		x	x	O	tr	tr					
164-410c	O	O		X		x	x	X	tr	tr					
164-410d	O	X		X		x	X	O	x	tr					

Specimen	Qtz	Pla	Bio	Mu	Hbl	Gar	Chl	Ep	Sph	Gra	Ca	Rut	Op	Other	Comments
Napeequa schist															
164-71	O	X	X		X	X	x	tr					o		
164-72	X	O	X		X	x	X	x					o		
164-73a	O	O	X	x	O	x	x	X		x			o		
164-73b	O	X	X	x	O	x	x	x		x					
164-73c	X	X	O	x	X	x	x	x		x			o		barom
164-73d	O	X	x		O	x	tr	tr				tr	o		
164-74a	x	X			O		x	X	x			tr	o		
164-74b	X	O	x		O		x	x	x				o		

Kindy Ridge Cont'd

Specimen	Qtz	Pla	Bio	Mu	Hbl	Gar	Chl	Ep	Sph	Gra	Ca	Rut	Op	Other	Comments
Napeequa schist															
164-75	O	X	X	X			x			X		tr			
164-76	O	X	X	x			x	x		X		x	o		
164-77a	O	X	X	x			tr			X	x				
164-77b	O	O		X						X	x		o		
164-78a	O	X	X		X		x	X	x						
164-78c	O	X	O		x		x	X	x						
164-79				O			X	X				tr			
164-411	X	X	O	X	tr			X			x		o		
164-412	O	X	X	x			x			x					

Illabot Creek

Specimen	Qtz	Pla	Bio	Mu	Am	Gar	Chl	Ep	Sph	Gra	Ca	Rut	Op	Other	Comments
Napeequa schist															
164-36a	O	X			O		O	x	tr						
164-36b	O	X		x			O	tr		O					
164-36c	O	X			O		X	X	x						
164-36d	X	O			O		X	O							
164-36e	O	X	X		O		x	X		x					
164-36f	O	X	x	x			O	x		X					
164-37b	O	X	O	x		X	x	tr		x			o		
164-37d	O	X	x			X	O	x					o		
164-38	O	X	X	X			X	x		X			o		
164-39a	O	X	x	X		X	X			X	x		o		
164-39b	O	X	x	X		X	X			X	X		o		

Jordan and Boulder Creek Ridge

Specimen	Qtz	Pla	Bio	Mu	Am	Gar	Chl	Ep	Sph	Gra	Ca	Rut	Op	Other	Comments
Napeequa schist															
164-18a	O		tr	O			O		x		x		o		
164-18b	X	x		X			O	O	x	x	tr	tr			
164-18c	O			x			x			X					
164-18d	x	X		X			O	O	x	x	tr				
164-21a1	O		x	x			tr	x	x	x			o		
164-21a2	O	x	x	x				x	x	x			o		
164-22	O		x	x			x			x					
164-23b	O	x	X		X			x	tr			tr			
164-24a	O			tr	X			X	x						
164-24b	O		x	x						x					

Specimen	Ant	Tlc	For	Op	Others	Comments
Serpentinite						
164-19	O			x		

APPENDIX 2
MINERAL COMPOSITIONS

Country Rock Thermobarometry Samples

174-118a

Mineral Formula

	biot	garn	plag	amph
Si	5.91	5.98	-	7.05
Al4	2.09	-	-	0.95
Al6	1.67	3.99	-	0.83
Ti	0.21	0.02	-	0.02
Fe2	2.40	4.18	-	1.78
Mg	2.75	1.04	-	2.69
Mn	0.01	0.19	-	0.02
Ca	-	0.61	0.25	1.83
Na	0.03	-	0.76	0.33
K	1.91	-	0.00	0.03
N	2	2	4	4

164-73c

Mineral Formula

	biot	garn	plag	amph
Si	5.96	5.98	-	6.46
Al4	2.04	-	-	1.54
Al6	1.52	3.98	-	1.08
Ti	0.24	-	-	0.06
Fe2	2.46	3.77	-	1.99
Mg	2.80	0.60	-	2.01
Mn	0.02	0.73	-	0.01
Ca	-	0.96	0.34	1.73
Na	0.02	-	0.67	0.54
K	1.96	-	-	0.04
N	4	3	4	3

174-33a

Mineral Formula

	biot	garn	plag	musc
Si	5.93	5.95	-	6.53
Al4	2.07	-	-	1.47
Al6	1.76	3.97	-	4.89
Ti	0.24	-	-	0.05
Fe2	2.74	4.91	-	0.11
Mg	2.27	0.83	-	0.13
Mn	0.01	0.14	-	0.00
Ca	-	0.24	0.34	-
Na	0.11	-	0.68	0.38
K	1.68	-	0.00	1.77
N	4	2	4	2

174-36c

Mineral Formula

	biot	garn	plag	amph
Si	6.01	5.93	-	6.53
Al4	1.99	-	-	1.47
Al6	1.41	4.03	-	0.94
Ti	0.31	-	-	0.10
Fe2	2.49	3.85	-	1.89
Mg	2.82	1.01 ~~2.14~~	-	2.14
Mn	0.01	.2 ~~0.02~~	-	0.02
Ca	-	1.02 ~~1.79~~	0.36	1.79
Na	0.04	~~0.49~~ 0	0.64	0.49
K	1.84	~~0.10~~ 0	0.00	0.10
N	4	3	4	3

biot = biotite, garn = garnet, plag = plagioclase, amph = amphibole,
musc = muscovite; N = number of microprobe spots sampled;
all garnets are rim compositions.

Country Rock Thermobarometry Samples Cont'd.

174-24

Mineral Formula

	garn	plag	amph
Si	5.86	-	6.39
Al4+	-	-	1.62
Al6+	4.03	-	1.01
Ti	-	-	0.08
Fe2+	3.95	-	2.01
Mg	0.73	-	2.00
Mn	0.37	-	0.03
Ca	1.18	0.38	1.87
Na	-	0.65	0.34
K	-	0.01	0.10
N	2	4	4

174-45b

Mineral Formula

	biot	garn	plag	musc
Si	5.96	5.91	-	6.67
Al4	2.04	-	-	1.33
Al6	1.69	4.03	-	4.81
Ti	0.24	-	-	0.05
Fe2	2.21	4.35	-	0.10
Mg	2.90	0.84	-	0.18
Mn	0.00	0.06	-	0.00
Ca	-	0.88	0.40	-
Na	0.07	-	0.59	0.40
K	1.71	-	0.00	1.73
N	4	4	2	2

174-8a

Mineral Formula

	biot	garn	plag	musc
Si	5.95	5.91	-	6.88
Al4	2.05	-	-	1.12
Al6	1.60	3.98	-	4.43
Ti	0.26	-	-	0.02
Fe2	3.32	3.61	-	0.43
Mg	1.72	0.38	-	0.37
Mn	0.02	0.28	-	0.00
Ca	-	1.93	0.37	-
Na	0.04	-	0.63	0.09
K	2.06	-	0.01	2.09
N	4	2	4	2

biot = biotite, garn = garnet, plag = plagioclase, amph = amphibole, musc = muscovite; N = number of microprobe spots sampled; all garnets are rim compositions.

APPENDIX 3
GEOCHEMICAL ANALYSIS

	unit	Downey Creek	Cyclone Lake	Bench Lake
	specimen	174-2a	174-33b	174-38b
Normalized Results (weight %)				
	SiO2	72.78	72.65	71.67
	Al2O3	15.37	16.37	15.99
	TiO2	0.21	0.26	0.30
	FeO	1.39	1.43	1.43
	MnO	0.02	0.03	0.02
	CaO	1.83	2.57	2.87
	MgO	0.23	0.41	0.68
	K2O	3.42	1.91	2.14
	Na2O	4.71	4.27	4.82
	P2O5	0.04	0.10	0.07
Trace Elements (ppm)				
	Ni	7	11	13
	Cr	1	6	17
	Sc	9	3	3
	V	0	13	32
	Ba	1786	750	971
	Rb	79	54	55
	Sr	534	557	593
	Zr	79	113	105
	Y	3	7	6
	Nb	2.3	4.1	4.5
	Ga	24	23	23
	Cu	9	11	10
	Zn	97	70	70
	Pb	13	10	12
	La	11	8	29
	Ce	11	27	17
	Th	3	4	3

Major elements are normalized on a volatile-free basis.
Total Fe is expressed as FeO.